

Time-evolution of ionization and heating around first stars and miniquasars

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ABSTRACT

A one dimensional radiative transfer code is developed to track the ionization and heating pattern around the first miniquasars and Population III stars. The code follows the evolution of the ionization of the species of hydrogen and helium and the intergalactic medium temperature profiles as a function of redshift. The radiative transfer calculations show that the ionization signature of the first miniquasars and stars is very similar yet the heating pattern around the two is very different. Furthermore, the first massive miniquasars ($\gtrsim 10^5 M_\odot$) do produce large ionized bubbles around them, which can potentially be imaged directly using future radio telescopes. It is also shown that the ionized bubbles not only stay ionized for considerable time after the switching off of the source, but continue to expand for a short while due to secondary collisions prompted by the X-ray part of their spectra. Varying spectral shapes also produced sizable variations in ionized fraction and temperature profile. We also compare the radiative transfer results with the analytical approximation usually adopted for heating by miniquasars and find that, because of the inadequate treatment of the He species, the analytical approach leads to an underestimation of the temperature in the outer radii by a factor ≈ 5 . Population III stars – with masses in the range of $10 - 1000 M_\odot$ and modelled as blackbodies at a temperature of 50000 K – are found to be efficient in ionizing their surroundings. The lack of very high energy photons limits the extent of heating of these first stars and have a distinctly different signature from that of the miniquasars. Observational effects on the 21 cm brightness temperature, the thermal and kinetic Sunyaev-Ze’ldovich effects, are also studied in the context of the upcoming radio and microwave telescopes like LOFAR and SPT.

Key words: quasars: general – cosmology: theory – observation – diffuse radiation – radio lines: general.

1 INTRODUCTION

Comprehending the end of the so called “dark ages of the Universe” through the process of reionization constitutes a very important step in our understanding of the formation and build up of structure in the Universe. It also provides a powerful constraint on various cosmological models (Tozzi et al. 2000; Bharadwaj & Ali 2005; Zaldarriaga, Furlanetto, & Hernquist 2004). Observation of this crucial epoch in the history of the Universe is possible through the redshifted 21 cm emission from neutral hydrogen as first recognized by Sunyaev & Ze’ldovich (1975) and further improved upon and developed by many authors like Hogan & Rees (1979), Scott & Rees (1990) and Madau, Meiksin, & Rees (1997).

One of the popular views on how reionization occurred is the following (Furlanetto, Zaldarriaga, & Hernquist 2004); first sources of light, be it Population III (hereafter, Pop III) stars, miniquasars or any other other source of radiation, created ionized bub-

bles. These ionized bubbles probably started to form around high density peaks, roughly at the same time, everywhere in the Universe. As the sources number of increased and since the expansion rate of these bubbles was greater than the Universe’s expansion, the bubbles overlapped around a certain redshift. A novel class of large radio telescopes like LOFAR^{1,2}, MWA³, 21CMA⁴ and SKA⁵ are being designed, among other things, to map the 21 cm emission from neutral diffuse inter galactic medium (IGM) at the Epoch of Reionization (EoR) as a function of redshift, where they will detect the statistical signature of the high redshift Universe as a function of z (Zaldarriaga, Furlanetto, & Hernquist 2004; Furlanetto, Zaldarriaga, & Hernquist 2004). The ultimate goal of these mega radio telescopes would lie in resolving and mapping

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¹ www.lofar.org

² www.astro.rug.nl/~LofarEoR

³ http://www.haystack.mit.edu/ast/arrays/mwa/

⁴ http://21cma.bao.ac.cn/

⁵ www.skatelescope.org

the ionized bubbles and their evolution around the first sources of UV radiation.

Recent observations show that quasars with black hole masses as large as $10^9 M_\odot$ have already existed at redshift 6 and higher (Fan et al. 2003, 2006) suggesting the existence of miniquasars that harbor intermediate mass black holes with masses in the range of $10^{3-6} M_\odot$ at very high redshifts ($z > 10$). A scenario in which a black hole starts accreting mass at very high redshift thus producing UV and X-ray radiation that ionizes and heats up its surrounding IGM has been studied by many authors (Ricotti & Ostriker 2004a,b; Nusser 2005; Furlanetto, Zaldarriaga, & Hernquist 2004; Wyithe & Loeb 2004; Furlanetto & Loeb 2002; Dijkstra et al. 2004). Many aspects of the above scenario are debatable, e.g., what was the primordial black hole formation mechanism (Begelman, Volonteri, & Rees 2006; Spaans & Silk 2006)? and what was the evolution rate of their mass densities as a function of redshift which varies dramatically depending on the model used (c.f., Begelman, Volonteri, & Rees (2006), Rhoads & Haehnelt (2006) and Zaroubi et al. (2007) for different scenarios)? Furthermore, the spectral indices of the power law spectral energy distribution of a quasar, even if marginally different, can suggest very different imprints. Also the accretion rate and lifetimes of these primordial objects are completely unknown.

Apart from these large potential variations in parameters within the scenario of miniquasars, we also have the distinctively different scenario of Pop III stars as the primary source of reionization (Benson et al. 2006; Whalen, Abel, & Norman 2004; Abel, Wise, & Bryan 2007; Ciardi, Ferrara, & White 2003; Barkana & Loeb 2001; Loeb 2006; Chen & Miralda-Escude 2006; Bromm, Kudritzki, & Loeb 2001; Kitayama et al. 2004; Wyithe & Loeb 2003). Within the context of Pop III stars there are many uncertainties that need to be considered. For example, the unknown blackbody temperature of the star (assuming they can be characterized by one), its mass, life-times, clustering properties and redshifts at which they start to appear.

In this paper, we try to fully explore the implications of varying the above mentioned parameters on the final maps of the 21 cm signal for individual objects that are initially surrounded by neutral IGM. In order to achieve a full sample of this parameter space it becomes imperative that a fast and realistic method of modelling these parameters is introduced. Previous simulations of radiative transfer in cosmological context and studies on the impact of first sources on the surrounding IGM, show that the regions that are ionized around these first sources, are almost spherically symmetric, e.g., Figure 7 of Kuhlen & Madau (2005). Thus we resorted to developing and using a 1-D radiative transfer code to study the ionizing fronts (I-front), their velocity, size, shape and so on.

Quick execution times and the simplicity in setting up the initial conditions allow us to simulate the influence of the miniquasars with varying masses for different redshifts, lifetimes and spectral indices. Specifically, we explore the influence of individual black hole masses ranging from $100 M_\odot$ to $10^8 M_\odot$, redshifts between 10 and 30 and lifetimes in the range of 3 to 20 million years. The influence of first stars on the IGM was explored with mass ranges of $10 M_\odot$ – $10^3 M_\odot$, whose luminosity is determined mainly by their mass (Schaerer 2002).

The upcoming radio telescopes like LOFAR, MWA, 21CMA and SKA will be used to observe the redshifted 21 cm from the dark ages and the epoch of reionization. Hence, trying to predict the topology, intensity and distribution of the ionized regions as a function of redshift is crucial in the development of sophisticated data analysis techniques to retrieve the 21 cm EoR signal. Given

the spatial resolution of these radio telescopes, it is very hard to differentiate between the ionization bubbles around miniquasars and Pop III stars. Chen & Miralda-Escude (2006); Kuhlen & Madau (2005); Zaroubi & Silk (2005) have suggested ways to differentiate between various sources of ionization. In this paper it is shown that the heating caused by these two possible ionization sources is significantly different especially at the early stages of the EoR, leading to different strengths of coupling between the spin and kinetic temperature which is reflected in the measured brightness temperature. Therefore we argue that this feature could, in principle, be used to distinguish between ionization sources.

The paper is structured as follows: In section §2 we detail the rate equations used in the simulations and also describe how we solve for the radial dependencies of the ionized fractions of the various species involved and of the temperature. Accuracy and reliability of the radiative transfer code developed were tested. Results of the two tests conducted, namely, propagation of the ionizing front into the mean non-expanding IGM and the Shapiro & Giroux case in which the IGM is expanding with the Universe, are presented in §3. §4 outlines some of the results obtained in the application of this code to power-law sources. A similar exercise is carried out for the case of stars and results discussed in §5. The coupling mechanisms between the spin and kinetic temperatures and its effect on the brightness temperature is discussed in §6. Other observables like the thermal and kinetic Sunyaev-Ze'ldovich effects caused by these sources are considered in §7. We present our conclusions and the possibilities of expanding this work further in §8. We also present a comparison of the heating profiles provided by the code developed here with an analytical approach developed earlier in the appendix §A.

2 SIMULATIONS

The results presented in this study are based on a 1-D radiative transfer (RT) code with which the evolution of HI, HII, HeI, HeII, HeIII, free electrons and temperature is monitored in time. In order to achieve this, we follow Fukugita & Kawasaki (1994), wherein a set of coupled differential equations (1 to 3 and 12) are solved. We follow Jones & Wyse (1985) and Fukugita & Kawasaki (1994) in treating hydrogen as two-level system plus a continuum.

For this study, in the case of miniquasars, we simply assumed that the density surrounding it is the mean density in an expanding Universe. For the case of stars, we assume an isothermal like profile of the form $\rho(r) [\text{cm}^{-3}] = 3.2 \times (91.5 \text{ pc}/r)^2$, as in Mellema et al. (2006), until the density reaches the mean IGM density, after which we set the density to that of the mean IGM. The cosmological parameters used here are those set by the WMAP 3rd year results (Spergel et al. 2007).

2.1 Rate equations

In the RT code we developed, the radiation is allowed to propagate radially with an underlying density profile, which in our case is the constant background IGM density. The code solves the following rate equations and finds the number density of each species in time and space:

$$\frac{dn_{\text{HII}}}{dt} = \Gamma_{\text{H}} n_{\text{HI}} - \alpha_{\text{HII}} n_{\text{e}} n_{\text{HII}} \quad (1)$$

$$\begin{aligned} \frac{dn_{\text{HeII}}}{dt} = & \Gamma_{\text{HeI}} n_{\text{HeI}} + \beta_{\text{HeI}} n_e n_{\text{HeI}} \\ & - \beta_{\text{HeII}} n_e n_{\text{HeII}} - \alpha_{\text{HeII}} n_e n_{\text{HeII}} \\ & + \alpha_{\text{HeIII}} n_e n_{\text{HeIII}} - \xi_{\text{HeII}} n_e n_{\text{HeII}} \end{aligned} \quad (2)$$

$$\begin{aligned} \frac{dn_{\text{HeIII}}}{dt} = & \Gamma_{\text{HeII}} n_{\text{HeII}} + \beta_{\text{HeII}} n_e n_{\text{HeII}} \\ & - \alpha_{\text{HeIII}} n_e n_{\text{HeIII}} \end{aligned} \quad (3)$$

$$\begin{aligned} \Gamma_{\text{HI}} = & \gamma_{2c} + \beta_{\text{HI}} n_e + \int_{E_{\text{HI}}}^{\infty} \sigma_{\text{HI}} N(E; r; t) \frac{dE}{E} + \\ & f_H \left[\int_{E_{\text{HI}}}^{\infty} \sigma_{\text{HI}} \left(\frac{E - E_{\text{HI}}}{E_{\text{HI}}} \right) N(E; r; t) \frac{dE}{E} \right] + \\ & f_H \left[\frac{n_{\text{HeI}}}{n_{\text{HI}}} \int_{E_{\text{HeI}}}^{\infty} \sigma_{\text{HeI}} \left(\frac{E - E_{\text{HeI}}}{E_{\text{HeI}}} \right) N(E; r; t) \frac{dE}{E} \right] \end{aligned} \quad (4)$$

$$\begin{aligned} \Gamma_{\text{HeI}} = & \int_{E_{\text{HeI}}}^{\infty} \sigma_{\text{HeI}} N(E; r; t) \frac{dE}{E} + \\ & f_{\text{He}} \left[\int_{E_{\text{HeI}}}^{\infty} \sigma_{\text{HeI}} \left(\frac{E - E_{\text{HeI}}}{E_{\text{HeI}}} \right) N(E; r; t) \frac{dE}{E} \right] + \\ & f_{\text{He}} \left[\frac{n_{\text{HI}}}{n_{\text{HeI}}} \int_{E_{\text{HeI}}}^{\infty} \sigma_{\text{HI}} \left(\frac{E - E_{\text{HI}}}{E_{\text{HeI}}} \right) N(E; r; t) \frac{dE}{E} \right] \end{aligned} \quad (5)$$

$$\Gamma_{\text{HeII}} = \int_{E_{\text{HeII}}}^{\infty} \sigma_{\text{HeII}} N(E; r; t) \frac{dE}{E} \quad (6)$$

where, n_{HI} , n_{HII} , n_{HeI} , n_{HeII} and n_{HeIII} are the neutral & ionized hydrogen, neutral, single and doubly ionized helium densities respectively. n_e is the total electron density given by $n_e = n_{\text{HII}} + n_{\text{HeI}} + 2n_{\text{HeII}}$. E_{HI} , E_{HeI} and E_{HeII} are the ionization energies for the corresponding species. β are the collisional ionization coefficients, α and ξ , the recombination coefficients, σ are the bound-free photo-ionization cross-sections, $\gamma_{2c} = \alpha_{\text{HI}}(T_\gamma) \times (m_e k T_\gamma / 2\pi)^{3/2} e^{-3.4\text{eV}/T_\gamma}$, is the photoionization coefficient due to background photons. The subscripts denote the species to which the coefficient belongs.

The radiation flux $N(E; r; t)$, is the same as in Zaroubi & Silk (2005);

$$N(E; r; t) = e^{-\tau(E; r; t)} \frac{Ag}{(r/Mpc)^2} I(E) \quad [\text{cm}^{-2}\text{s}^{-1}] \quad (7)$$

where $I(E)$ is the spectral energy distribution, Ag , is the normalization coefficient calculated as;

$$Ag = \frac{E_{\text{total}}}{\int_{\text{Range}} I(E) dE}, \quad (8)$$

where E_{total} is the total energy output of the *first* objects within the energy range (E_{range}), and the optical depth $\tau(E; r; t)$ is given by;

$$\tau(E; r; t) = \sum_i \int_r \sigma_i(E) n_i(r; t) dr \quad (9)$$

Where the sum is over all species. The effects of secondary ionizations – due to the kinetic energy carried by ejected electron – have been folded in through the terms f_H and f_{He} . These two terms depend of the ionization state of the medium and given by (Shull & van Steenberg 1985);

$$f_H = 0.3908(1 - x_{\text{ion}}^{.4092})^{1.7592} \quad (10)$$

and,

$$f_{\text{He}} = 0.0554(1 - x_{\text{ion}}^{.4614})^{1.6660}. \quad (11)$$

Here x_{ion} is the ionized fraction of hydrogen. For ionization, this effect becomes significant when dealing with very high energy photons ($> 1\text{KeV}$) and when the medium is neutral to partially ionized.

Note here that the causality aspect of the code comes in through the ionization terms. Because, as will be discussed later, we are presenting a grid code in which the memory of the ionization history of all the cells prior to the cell under consideration is embedded in the optical depth, which in turn dictates the amount of radiation available to ionize a particular cell.

Fits for the collisional ionization and recombination coefficients were obtained from the appendix of Fukugita & Kawasaki (1994). The photoionization cross-sections though are obtained using the fitting formula of Verner et al. (1996). For the exact form of these fitting function we refer the reader to these two papers.

The temperature evolution is monitored by coupling equations 1 to 3 with the equation below.

$$\begin{aligned} \frac{3}{2} \frac{d}{dt} \left(\frac{kT_e n_B}{\mu} \right) = & f_{\text{Heat}} \sum_{i=\text{HI}, \text{HeI}, \text{HeII}} n(i) \int \sigma_i(E - E_i) N(E; r; t) \frac{dE}{E} \\ & + \frac{\sigma_s n_e}{m_e c^2} \sum_{i=\text{HI}, \text{HeI}, \text{HeII}} \int N(E; r; t) (E - 4k_B T) dE \\ & - \sum_{i=\text{HI}, \text{HeI}, \text{HeII}} \zeta_i n_e n(i) \\ & - \sum_{i=\text{HII}, \text{HeII}, \text{HeIII}} \eta_i n_e n(i) \\ & - \omega_{\text{HeII}} n_e n_{\text{HeIII}} \\ & - \sum_{i=\text{HI}, \text{HeI}, \text{HeII}} \psi_i n_e n(i) \\ & - \theta_{\text{H}} [n_{\text{HII}} + n_{\text{HeII}} + 4n_{\text{HeIII}}] n_e \\ & - 2 \frac{\dot{a}}{a} \left(\frac{kT_e n_B}{\mu} \right) \end{aligned} \quad (12)$$

The form of equation 12 is identical to that of Fukugita & Kawasaki (1994) except for the inclusion of the Compton heating term (ref. Madau & Efstathiou 1999) which become important as we approach the source which is placed at the centre, i.e., radius equals zero. In the above equation, E_i is the threshold energy of ionization of the i^{th} species which is either HII, HeI or HeII. σ_s , is the Thompson scattering cross-section

of an electron ($\sigma_s = 6.6524 \times 10^{-25} \text{ cm}^2$). ζ_i and η_i are the collisional-ionization cooling and recombination cooling coefficient, respectively. ω_{HeII} is the dielectronic recombination cooling coefficient due to HeII. ψ_i is the collisional excitation cooling coefficient and θ_{ff} the free-free cooling coefficient. Cooling due to Hubble expansion is accounted for by the term, $\frac{\dot{a}}{a} \left(\frac{kT_e n_B}{\mu} \right)$ where $\frac{\dot{a}}{a} \equiv H$ is the Hubble constant. The factor f_{Heat} is the amount of heat deposited by secondary electrons and is given by;

$$f_{Heat} = \begin{cases} 0.9971(1 - (1 - x_{ion}^{0.2663})^{1.3163}), & \text{if } x_{ion} > 10^{-4} \\ 0.15 & \text{if } x_{ion} \leq 10^{-4} \end{cases}$$

The above expression is an extrapolation of fitting formula used in Shull & van Steenberg (1985) and the results of their calculations as plotted in their Figure 3. We here use the fact that the heating fraction never really goes to zero but saturates around a value of 0.15. The fitting formulas used in Shull & van Steenberg (1985) are appropriate for relatively high energies (typically $> 100 \text{ eV}$).

$$f_H(x_{ion}, E) = 0.3908(1 - x_{ion}^{0.4092a(x_{ion}, E)})^{1.7592}, \quad (13)$$

where $a(x_{ion}, E)$ is,

$$a(x_{ion}, E) = \frac{2}{\pi} \arctan \left[\left(\frac{E}{0.12 \text{ KeV}} \right) \left(\frac{0.03}{x_{ion}^{1.5}} + 1 \right)^{0.25} \right]. \quad (14)$$

Notice that the inclusion of an energy dependent fitting formula for the fraction of energy that goes to ionization, as in equation 13 (Dijkstra, Haiman, & Loeb 2004), does not alter the result significantly. This is due to the fact that the lower energy photons are trapped close to the vicinity of source for ionization and the remaining photons are of relatively high energies for which the fitting formula of Shull & van Steenberg (1985) holds.

The integrals in equation 1 to 12 are pre-calculated and tabulated as a function of $n_i x_i$, where the index 'i' refers to HI, HeI or HeII. n_i refers to the abundances and x_i the ionized fraction of the i th species. In other words we are tabulating the integrals as a function of optical depth per unit distance. Therefore in principle we should have a three dimensional table, as is commonly used (Iliev et al. 2006). But the integration table in our implementation is at most two dimensional. We get around using three dimensional tables by utilizing the fact that the functional form for the photoionization cross-sections of H I and He II are the same except for a constant difference (see equations (B13) and (B16) of Fukugita & Kawasaki 1994).

2.2 The Algorithm

The aim of the radiative transport code developed is to compute the fraction of the ionization for the species of hydrogen and helium and the temperature for points along a radial direction away from the source, at various times. This was achieved by solving the time dependent rate equations (equations 1-12) using the ODEINT routine of Numerical Recipes (Press et al. 1992), using the implicit scheme of integration for *stiff* equations. The entire code was developed in ANSI C.

Figure 1 shows the basic steps involved in the solution of these rate equations. Firstly, the direction radial to the source is gridded into cells, the sizes of which are decided as described later. The inputs to the code at this stage are the parameter space we desire to probe in this study which includes the spectrum, masses of the sources and the redshifts at which these sources switch on. The

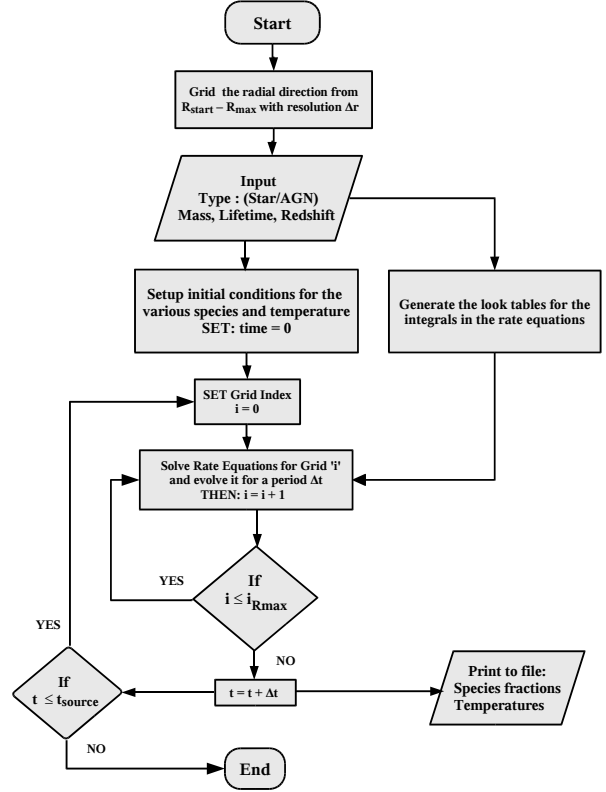


Figure 1. Flowchart outlining the basic modules in the algorithm implementing the radiative transfer code.

spectrum of the sources, broadly speaking are classified into power-law and blackbody. The slopes of the power law and the temperature of the blackbody can be set to any desired value. Once the spectrum of the source is known, a lookup table for the values of the integrals appearing in the rate equation is created.

Before the start of the simulation, the initial conditions are setup as follows. The region around the source is set to be completely neutral with the primordial abundance fraction of hydrogen and helium. All species therefore have densities corresponding to that of the IGM at that epoch, $n_H(z) = n_H(0)(1+z)^3$, $n_{He}(z) = n_{He}(0)(1+z)^3$, where $n_H(0) = 1.9 \times 10^{-7} \text{ cm}^{-3}$ and $n_{He}(0) = 1.5 \times 10^{-8} \text{ cm}^{-3}$ are the IGM densities at redshift zero of hydrogen and helium respectively or the initial density profile could also be set according to a profile as in equation 21. Abundances of all singly and doubly ionized species n_{HI} , n_{HeII} , n_{HeIII} and electron density n_e is set to zero. Initial kinetic temperature $T_e = T_{CMB}(z)(1+z)^2/(1+250)$. Here we have assumed that the kinetic temperature of the gas was coupled to the CMB temperature (T_{CMB}) till a redshift of 250, after which the T_{CMB} continued to fall off as $1/(1+z)$ and T_e like $1/(1+z)^2$.

We start our simulation at R_{start} , typically 0.1 physical kpc from the location of the source. All hydrogen and helium are assumed to be completely ionized inside this radius R_{start} . The outcome of the calculations for different choices of R_{start} has been

tested and, for the choice made in this paper, found to converge to the required accuracy.

Each cell is then updated for time Δt , which again is chosen based on a convergence criterion. This Δt is not the intrinsic time-step used to solve the differential equation itself because that is adaptive in nature and varies according to the tolerance limit set in the ODE solver. On the other hand, the Δt here decides for how long a particular cell should evolve before moving on to the next. For example, we cannot evolve the first cell for the entire lifetime of the source and move on to the next cell. Therefore, Δt is decided by reducing it by half each time until two consecutive runs with Δt and $\Delta t/2$ give the same final result for the ionized sphere within a tolerance limit. As eluded to before, the code is causal in the sense that a cell $i+1$ is updated after cell i . Note that the light travel time is not taken into consideration explicitly since the ionization front (I-front) is very subluminal. Hence, all cells are updated for time $n\Delta t$ at the n^{th} time-step.

After all cells until the last cell $i_{R_{\text{max}}}$ are updated for time Δt , the resulting values are stored and then passed on as initial conditions for the evolution of the cell in the next Δt interval of time. The update of all n_{cell} is repeated n times such that $n\Delta t = t_{\text{quasar}}$, where t_{quasar} is the life time of the miniquasar. The various quantities of interests can be stored in a file at intervals of choice.

A radial coverage of R_{max} is chosen *a priori* which, depending on the problem, can be set to any value. Typically we do not need to go above ten comoving mega-parsecs. This radius is then gridded equally with a resolution of Δr , which like the time resolution, is decreased to half its value until it meets a given convergence criterion, which here is that the final position of the I-front is accurate within 0.5%. For a typical run, which normally takes about 100 time steps, this criterion gives an accuracy of about 5×10^{-5} per time step.

The block computing the solution of the rate equations in Figure 1 requires further explanation. Once the spatial resolution is set by following the procedure described above, we compute for every cell, $\sum_1^{j-1} (n_i x_i)_s$, where j is the grid-cell under consideration, and these computed sums are used to evaluate the values of the integrals in equation 1 to 12 from pre-computed tables through a simple polynomial interpolation. The initial conditions and the value of the integrals are passed to the solver ODEINT (Press et al. 1992) with the *driver* to solve the *stiff* equations. At the end of this run all cells are updated for a time Δt .

3 TESTING THE CODE

In order to examine the performance of the code we carry out three tests. The first test is against the analytical form of the velocity of the I-front with constant background density and central source emitting a fixed number of photons, namely, the Strömgen sphere case. The second, is to compute the I-front velocity around a source again with a constant photon flux but with the background density evolving with redshift. This is then compared with the analytical solution of Shapiro & Giroux (1987). In both these cases the I-front is defined as the position at which the ionized and neutral hydrogen fractions are equal. The third test was a comparison between an analytical model of heating (Zaroubi et al. 2007) and the RT code. The results agree well except in the discrepancy are discussed in the Appendix.

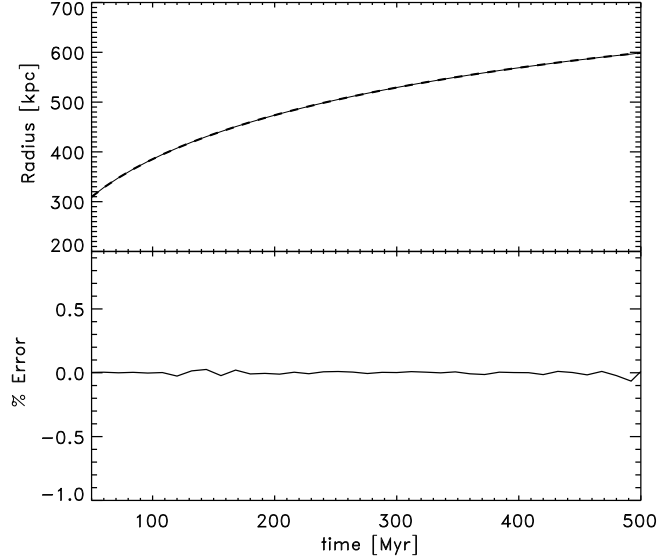


Figure 2. Top panel shows the simulated (solid) and the theoretical (dashed) results of the evolving I-front in a uniform background. This simulation include only hydrogen of constant density (i.e., no expansion).

3.1 Test-1: I-front velocity in simple cosmology

The first problem was to test the expanding HII bubble around a source that produces a fixed number of photons per unit time. Analytically, the position r_I and velocity v_I of the I-front can be written as:

$$r_I = r_s [1 - \exp(-t/t_{\text{rec}})]^{1/3}, \quad (15)$$

$$v_I = \frac{r_s}{3t_{\text{rec}}} \frac{\exp(-t/t_{\text{rec}})}{[1 - \exp(-t/t_{\text{rec}})]^{2/3}}. \quad (16)$$

Where r_s is the Strömgen radius (Dopita & Sutherland 2003); $r_s = \left[\frac{3\dot{N}_\gamma}{4\pi\alpha_B(T)Cn_H^2} \right]^{1/3}$; $t_{\text{rec}} = [C\alpha_B(T)n_H]^{-1}$, is the recombination timescale; n_H , the neutral hydrogen density; C is the clumping factor and $\alpha_B(T) = 2.6 \times 10^{-13} (T/10^4)^{-0.85} \text{ cm}^3 \text{ s}^{-1}$ is the hydrogen recombination coefficient at temperature T . The parameters used for this example are: $\dot{N}_\gamma = 10^{54} \text{ s}^{-1}$, $C = 5$, $\alpha_B = 2.6 \times 10^{-13} \text{ cm}^3 \text{ s}^{-1}$ and $n_H = 1.87 \times 10^{-4} \text{ cm}^{-3}$.

The solid line in Figure 2 is plotted based on equation 16 and the dashed line represents the numerical solution to the problem. The numerical solution obtained by the RD code is within 0.1% of the theoretical value.

3.2 Test-II: The Shapiro & Giroux test: Ionization front in an expanding Universe

Shapiro & Giroux (1987) derived an analytical solution for the position of the I-front as a function of cosmic time in an expanding Universe that contains only hydrogen. The solution is of the form,

$$y(t) = \lambda e^{\lambda t_i/t} [t/t_i E_2(\lambda t_i/t) - E_2(\lambda)], \quad (17)$$

where $y(t) \equiv (r_I(t)/r_{s,i})^3$, t_i is the age of the Universe at the time the source has turned on and r_I and $r_{s,i}$ are the comoving I-front position radially from the centre of the source and the initial Strömgen radius $(3\dot{N}_\gamma/C\alpha_B(T)n_H^2)^{1/3}$, respectively. Here n_H is the comoving density of hydrogen at source turn-on time. $\lambda \equiv t_i C\alpha_B(T)n_H$, is basically the ratio between cosmic source

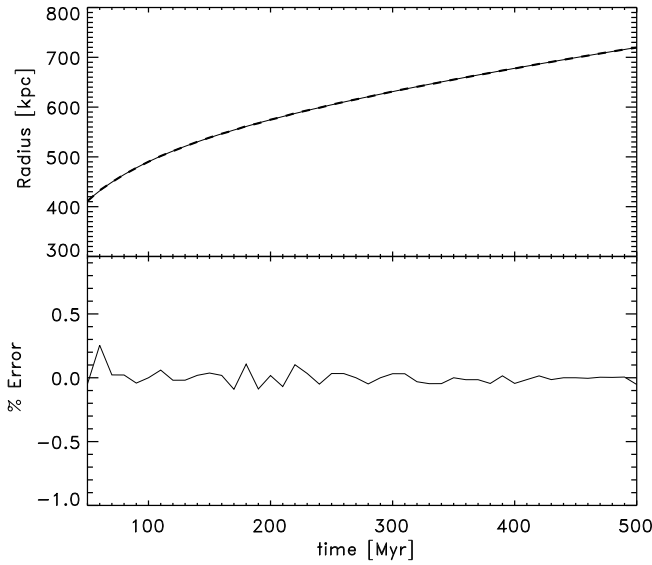


Figure 3. Top panel shows the simulated (solid) and the theoretical(dashed) results of the evolving I-front in an expanding Universe with background density being that of the IGM at that epoch.

turn-on time and the recombination timescale. $E_2(x)$ is an exponential integral of the form $E_2(x) = \int_1^\infty e^{-xt}/t^2 dt$.

Result of the test is plotted in Figure 3. The numerical and analytical solutions here also agree to within a couple of tenth of a percent throughout the evolution of the I-front.

4 APPLICATION TO POWER-LAW SOURCES (MINIQSOS)

Sources of ionizing radiation with a power-law spectral energy distribution has been considered by many authors (e.g., Madau, Meiksin, & Rees (1997); Kuhlen & Madau (2005); Fukugita & Kawasaki (1994); Nusser (2005); Zaroubi & Silk (2005); Zaroubi et al. (2007)). The radiative transport code is applied to these power-law sources where the ionization and heating patterns around them are studied as a function of their spectral index, mass and redshifts. For some of the plots in this section we have assumed masses of quasars in the order of $10^6 M_\odot$. Although recent works like Volonteri, Lodato, & Natarajan (2007) does show that there could be relatively massive blackholes at early redshifts, a $10^6 M_\odot$ would be unlikely. But we have included this case in our discussion for a completeness in spanning the parametre space and also to clearly distinguish the various effects of these sources on the IGM. In the following subsections we introduce and discuss our main findings.

4.1 Energy spectrum the miniquasar

Recent observations and catalogues published in the literature (Vanden Berk et al. 2001; Vignali, Brandt, & Schneider 2003; Laor et al. 1997; Elvis et al. 1994), suggest that the energy spectrum of quasars follows a power-law of the form $E^{-\alpha}$. Specifically, we explore two types of power law spectra:

$$I(E) \propto E^{-\alpha} \begin{cases} \text{if } 10.4\text{eV} < E < 1\text{keV (LE case);} \\ \text{if } 200\text{eV} < E < 1\text{keV (HE case).} \end{cases}$$

(18)

The value of α is fixed to unity for most of the study, although in section 4.4 we do briefly discuss the effects of varying this parameter. LE and HE stands for the 'Low Energy' and the 'High Energy' lower limits to which the spectral energy distribution extends. The HE case is considered in order to take into account, in an approximate manner, the possibility of the lower energy photons being absorbed in the close vicinity of the source. Instead of single slope one can also adopt multi-slope spectral templates (Sazonov, Ostriker, & Sunyaev 2004) but this is not done in this study.

The miniquasars are assumed to accrete at a constant fraction ϵ (normally 10%) of the Eddington rate. Therefore, the miniqso luminosity is given by:

$$L = \epsilon L_{\text{edd}}(M) \quad (19)$$

$$= 1.38 \times 10^{37} \left(\frac{\epsilon}{0.1} \right) \left(\frac{M}{M_\odot} \right) \text{erg s}^{-1}. \quad (20)$$

The luminosity derived from the equation above is used to normalize the relation in 18 according to equation 8. The normalization, both for the HE and LE case, is done for an energy range of 10.4 eV to 1 keV. Simulations were carried out for a range of masses between 10 and $10^6 M_\odot$. Although the number of photons at different energies is a function of the total luminosity and spectral index, if we assume that all photons are at the hydrogen ionization threshold, then the number of ionizing photons thus obtained for the mass range given above is in the order of 10^{50} to 10^{55} . These are of the same order of magnitude of the number of ionizing photons being employed for simulations by various authors, Mellema et al. (2006), Kuhlen & Madau (2005), for example.

4.2 Radial profile of species' fraction

Plotted in Figures 4 and 5 are snapshots of the neutral fraction as a function of the radial distance away from the centre of the black-hole for two different cases. The first (Fig.4) is the HE case, i.e., without low energy photons. Whereas, the second (Fig.5) is for the LE case, i.e., the photon energy range spans 10.4 eV to 10^4 eV. As indicated on the Figure, each panel corresponds to a different mass. The lines in each panel corresponds to snapshots of the neutral fraction at 1, 3, 5 and 10 Myr. In both cases the sources are turned on at a redshift of 20.

Figure 5 clearly shows that the size of the ionized regions are substantially larger than those in Figure 4. Even the 1000 solar mass miniqso produce regions that are tens of kpc in physical size. This is due to the increase in the number of photons in the lower energy (LE) range (13.6 to 200 eV), which increases the probability of a photon - atom interaction relative to the HE case ($\sigma \propto E^{-3}$). Equilibrium is only reached when the mini-quasar life-time approaches the recombination time-scale. Since the problem is set in an expanding Universe we never actually reach an equilibrium solution (Shapiro & Giroux 1987). We see that the ionized bubble gets to a couple of hundred kpc for the case of high energy photons and to more than 0.5 Mpc for $10^6 M_\odot$ miniqsos with low energy photons. All distances plotted in the Figures are physical unless specified otherwise.

The abundance of HI, HII, HeI, HeII and HeIII as a function of radial distance are tracked in time. Figures 6 and 7 shows the

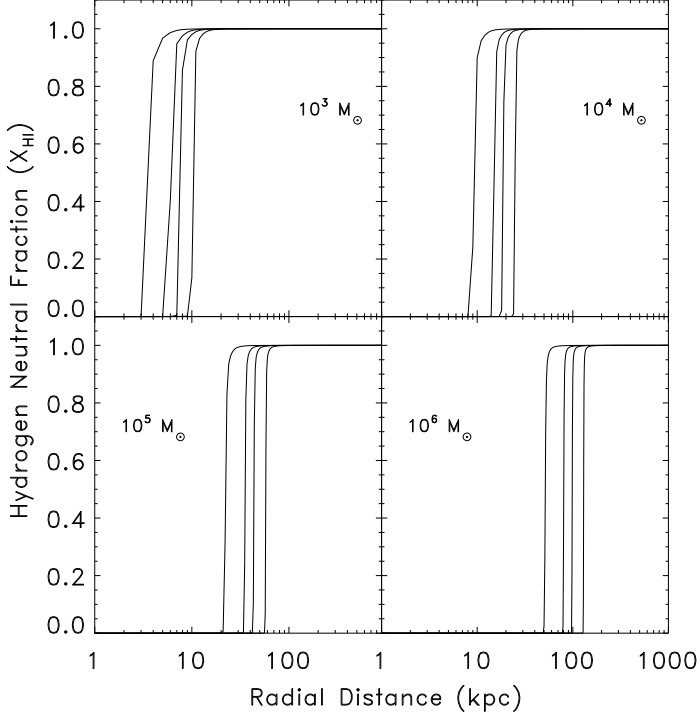


Figure 4. The neutral hydrogen fraction as a function of distance from the centre of the black hole with masses $10^3, 4, 5, 6 M_{\odot}$ (top-left to bottom right panel) at a redshift $z = 20$ is shown. Four lines in each panel indicates the position of the I-front after 1, 3, 5 and 10 Myr. These are miniquasars with no UV ionizing photons. ($200\text{eV} < E < 10^4\text{eV}$).

fraction of these species after 10 Myr of evolution as a function of radius. The miniquasar is switched on at redshift of 20.

The interplay between the evolution of these species among each other and with the gas temperature provides us with rich and interesting structures in profiles. Miniquasars of 10 and 100 solar masses are not able to produce substantially high number of ionizing photons and hence the ionized regions around them are relatively small. However, miniquasars of higher masses like 10^5 and 10^6 solar masses produce ionized bubbles of a couple of comoving megaparsecs.

An interesting detail apparent in these Figures is that the HeI I-front exceeds that of the HI. Explanation for this lies in the fact that we have relatively high energy photons ($E > 50\text{ eV}$) and the cross-section of HI is much smaller than HeI, $\sigma_{\text{HeI}}(E)/\sigma_{\text{HI}}(E) \approx 20$ at an energy $E = 50\text{ eV}$. Therefore, the probability of high energy photons being capture by HeI is higher, increasing the helium I-front distance from the centre.

Results are shown for the HE (6) and LE (7) cases. As expected the ionized fronts of HI and HeI have travelled a much greater distance in the LE case. This is consistent because the HE spectrum is not only devoid of hydrogen ionizing photons but also lacks helium ionizing photons (54.4 eV).

Another point to notice, is the visible excess of HI fraction in the HE spectrum just before the full ionization front in Figure 4, especially at the 10 Myrs curves. We interpret this excess as a result of the interplay between the increase of HeII and decrease of HeIII as seen in Figure 6 thus increasing the HI recombination rate on the one hand and decreasing photon flux as a function of radius on the

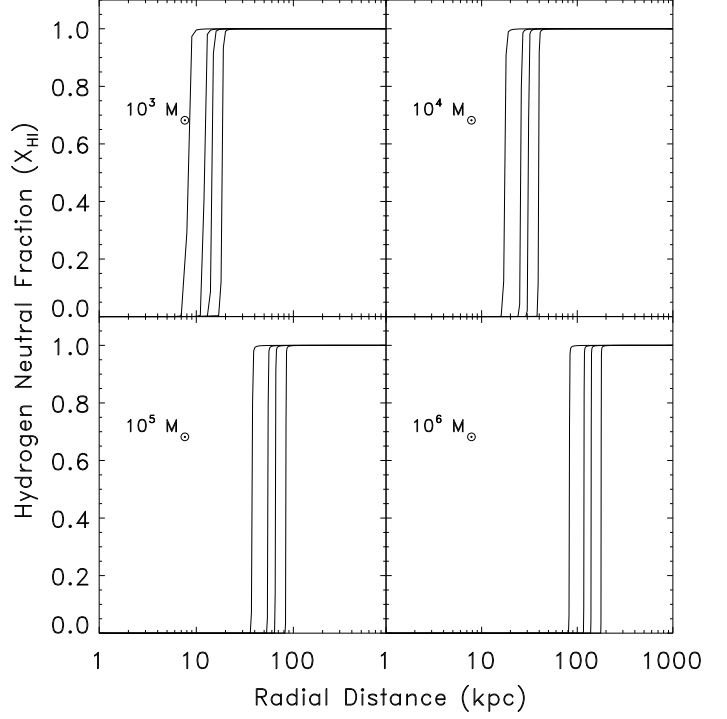


Figure 5. Same as in fig.4 but now including UV ionizing photons ($10.4\text{eV} < E < 10^4\text{eV}$).

other. This interpretation is supported by the weakening of the HI excess feature as a function of black hole mass. The phenomena is not manifested in the LE spectrum (Figure 5) due to the ionization efficiency of the UV photons.

4.3 The kinetic temperature profile

The heating and cooling terms included in equation 12 are coupled with the rate equations 1 to 3. The principal heating terms are the bound free and Compton heating. Bound free heating is by far the most dominant, although towards the centre Compton heating does become important.

Figures 8 and 9, corresponding to the HE and LE cases respectively, show the temperature profile for masses from $10M_{\odot}$ to 10^6M_{\odot} for four different redshifts. The snapshot is taken after 3 Myrs of evolution.

Although there is a substantial change in the ionization profiles (sizes of the ionized spheres), the heating remains more or less the same except for a few details. The flux of high energy photons, those responsible for the dominant secondary heating is abundant causing a sort of invariance in the extent of heating in both cases. Miniqs of high masses do maintain an extended volume of high temperatures, in some cases up to 5 comoving Mpc. If this indeed is the case at relatively low redshifts like around six, then they will be observable in the Sunyaev-Ze'dovich effect as discussed in section §7

The four panels corresponding to different redshifts do not show a significant difference in the heating or its extent. Whereas the ionized bubbles (Fig. 4 and/or 5) are strongly dependent on the redshift. This is due to the fact that lower energy photons (responsible for ionizing) see a much higher optical depth in neutral hydrogen than do high energy photons. Thus an increase in density

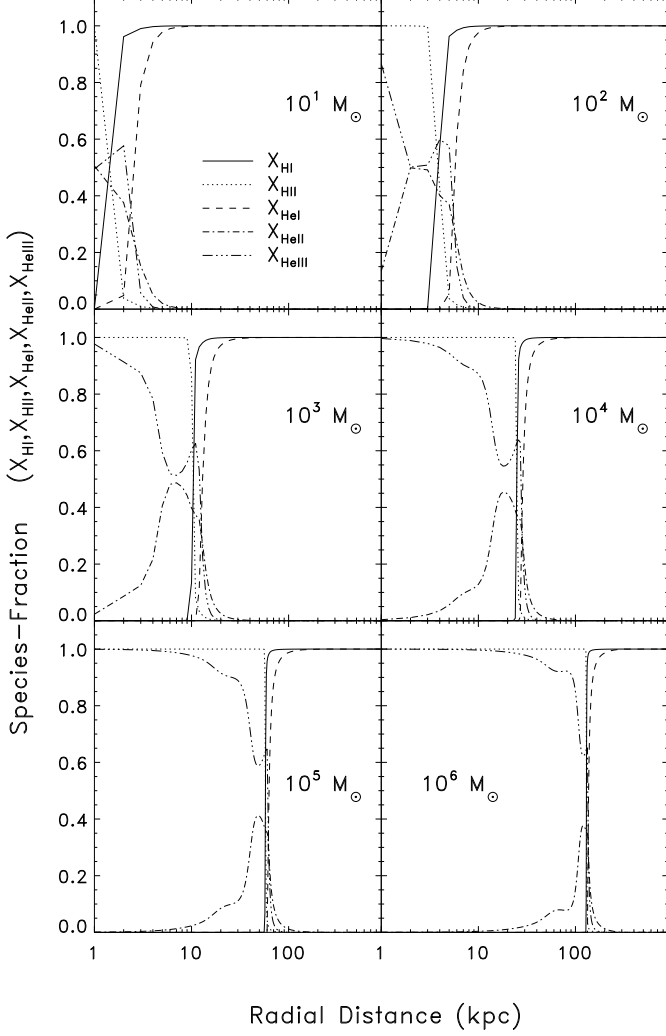


Figure 6. Fraction of various species ($x_{\text{HI}}, x_{\text{HII}}, x_{\text{HeI}}, x_{\text{HeII}}, x_{\text{HeIII}}$) as function of distance from the centre of the black hole with masses $10^{1,2,\dots,6} M_{\odot}$ (top-left to bottom right panel) at a redshift $z = 20$. These are snapshots after 10 Myr of evolution. Mini-quasars have no UV ionization energy ($200\text{eV} < E < 10^4\text{eV}$).

by an order of magnitude (from $z=10$ to $z=25$) does not alter the heating considerably.

4.4 Influence of different spectral energy distributions

Throughout our study in this paper we have dealt with $\alpha = 1$ case for equation 18. Here we explore the possibility of other indices for the power law. As an example we plot (ref. Fig. 10) the size of the ionized bubbles after 10 Myr as a function of α around a quasar with central black hole of $10^5 M_{\odot}$ for four different redshifts as indicated in the figure. Figure 10 shows that the size of the ionized bubble⁶ increases with α . This is expected because an increase in α for the same given normalization concentrates more photons at the low energy end, i.e., around 13.6 eV and fewer high energy

⁶ We define the size of the ionized bubble as the position of the I-front when the ionized fraction is 0.5 for hydrogen

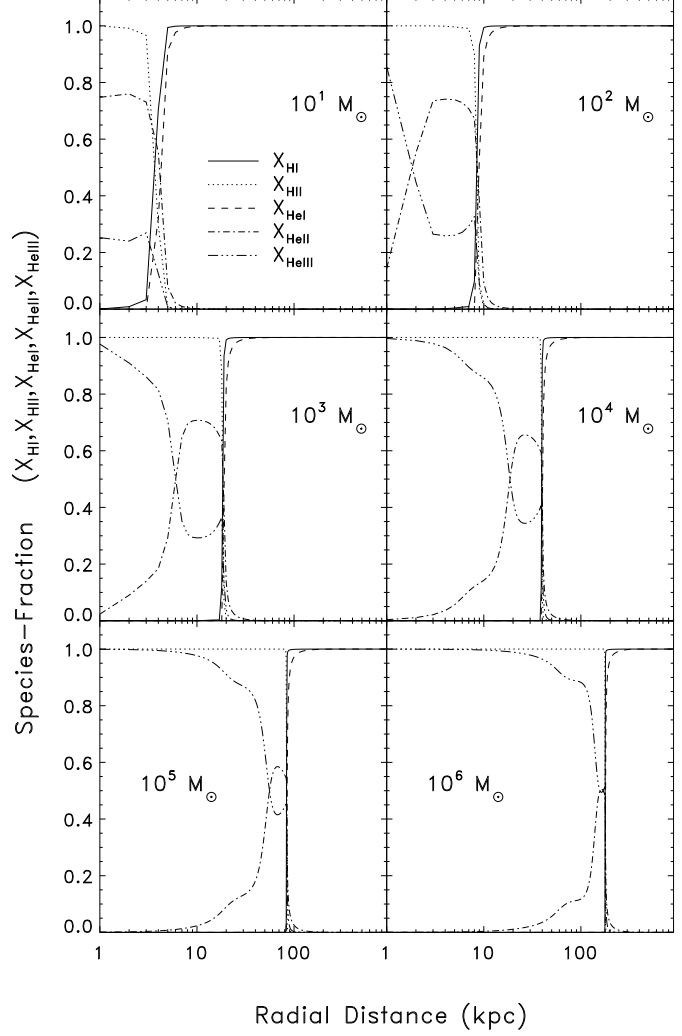


Figure 7. Same as in fig.6 but now including UV ionizing photons ($10.4\text{eV} < E < 10^4\text{eV}$).

photons. Thus, for higher α , one expects more ionization and less heating. This indeed is reflected in Figure 11.

The central regions are heated more or less to the same extent. In order to see the significant difference we have only plotted the distances between 100 and 1000 kpc physical. It is clearly seen that for steeper slope heating drops considerably.

4.5 Life-time & Duty-cycle of mini-quasars

Wyithe & Loeb (2002) produce analytical estimates of the quasar-life time and duty cycle (see their Figure 3). Certainly this sort of periodic switching on and off of the quasar leaves an imprint on the IGM. We simulate a case wherein the quasar duty cycle is 100 Myr with an active phase of 10 Myr at the start of the cycle.

Recombination time-scales are orders of magnitude larger than the ionization timescales at the mean densities of the IGM. As a result, once the IGM is ionized by a source with finite life time (say 10 Myr), it takes considerably long time for the IGM to recombine, leaving behind a bubble of ionized gas. Figure 12 shows the ionized fraction and the temperature profile just after the source is switched off at 10 Myr, than at 50 Myr and at the end of the duty

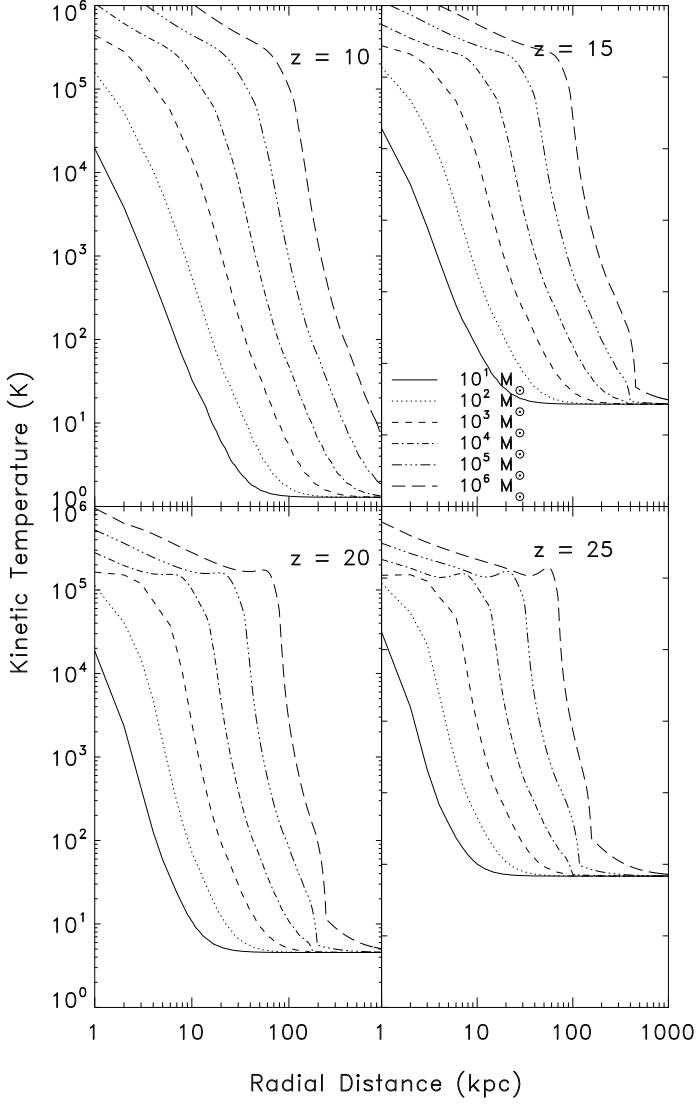


Figure 8. Radial profile of Kinetic temperature T_e for black hole with masses $10^1, 2, \dots, 6 M_\odot$ at 4 different redshift $z = 10, 15, 20, 25$ (top-left to bottom right) after 3 Myrs is shown. The spectrum of these quasars include only high energies.

cycle which is 100 Myr. The source is a miniqso of a $1000 M_\odot$ at redshift 20.

There are a couple of points to be noted here. One is the fact that the I-front position is further away at 50 and 100 Myr than at 10 Myr although the source was switched off after 10 Myr. This propagation of the I-front in the absence of photons from the source is attributed to the ionization due to collisions. This continues until the temperature drops sufficiently so that collisions become ineffective. In fact before the IGM recombines completely the quasar is switched on again. Thus we see⁷ that the ionizing front expands during the on-time, stands still around the same position during the off-time and continues to expand during the next on-time and so on.

⁷ movies created from the simulation can be obtained by contacting the authors

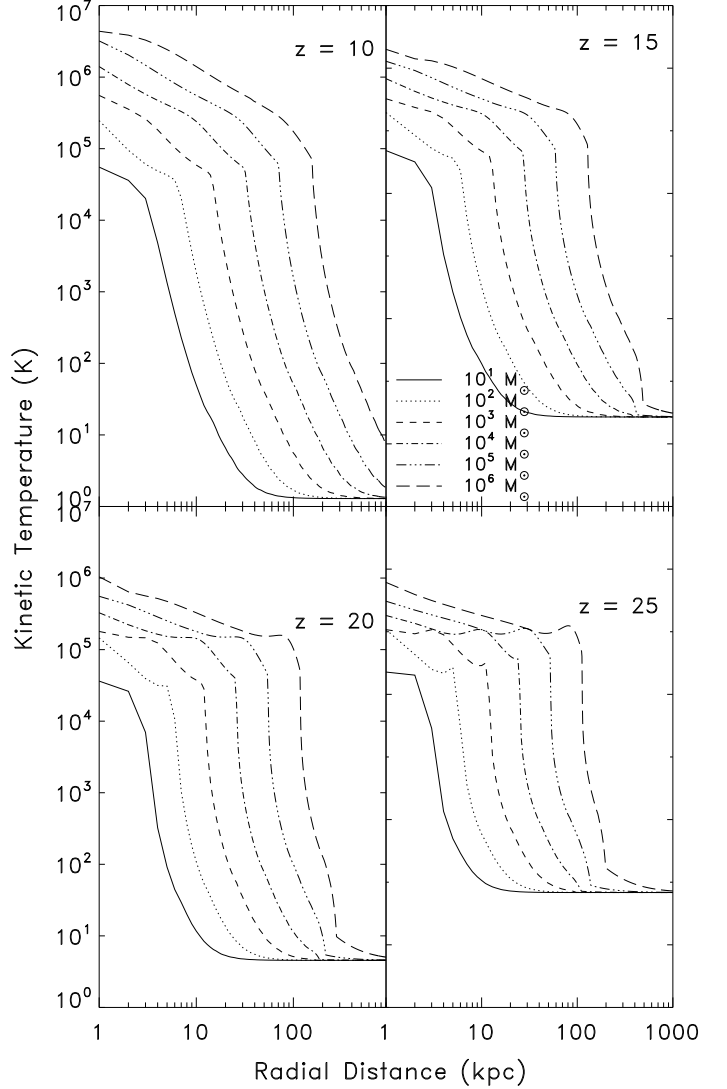


Figure 9. Same as in fig.8 but these quasars do include the low energy photon.

The drop in temperature on the other hand is easily seen within this turn-off period. Compton cooling is the dominant sink for the temperature. Also we see that the regions close to the centre remain relatively more ionized than the rest. This is again a consequence of the temperature profile. Regions with higher temperature continues to be ionized for longer periods.

All of the analysis performed thus far was done by embedding the source in a uniform background. But we know that objects like quasars are preferentially formed in overdense regions. In order to test the impact of different overdensities on the I-front position and temperature produced by a quasar we embed the quasar in a background that is 1, 10 and 100 times the mean IGM density. The results are shown in Figure 13. The miniqso has a $1000 M_\odot$ black hole at the centre and is at a redshift of 10 and contains only the high energy photons. As expected the ionization fronts could penetrate less at higher densities. But the recombination rate is much greater at higher densities. This is seen in the top right panel corresponding to 100 Myr as the I-front corresponding to a clumping factor of a 100 has recombined much more. On the other hand the

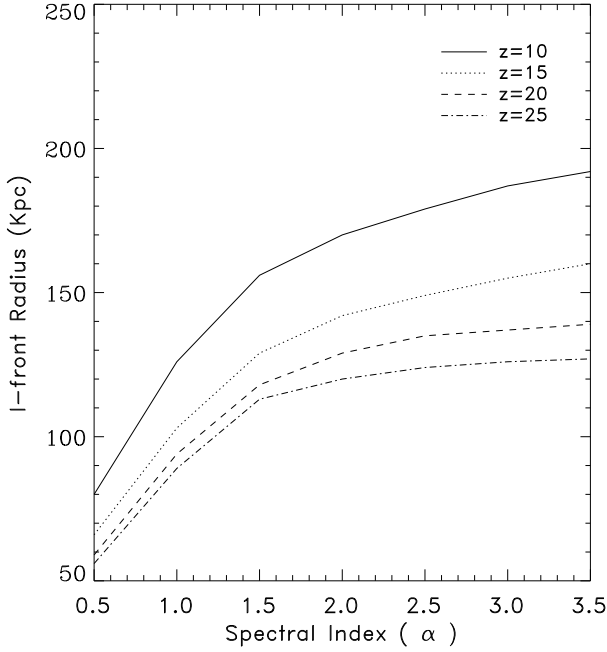


Figure 10. Position of the I-front is plotted in physical size as a function of spectral index α , 10 Myr after the quasar was switched on. Note that the sizes of the ionized region plateaus after about $\alpha = 2.5$. The black hole in the centre is of $10^5 M_\odot$.

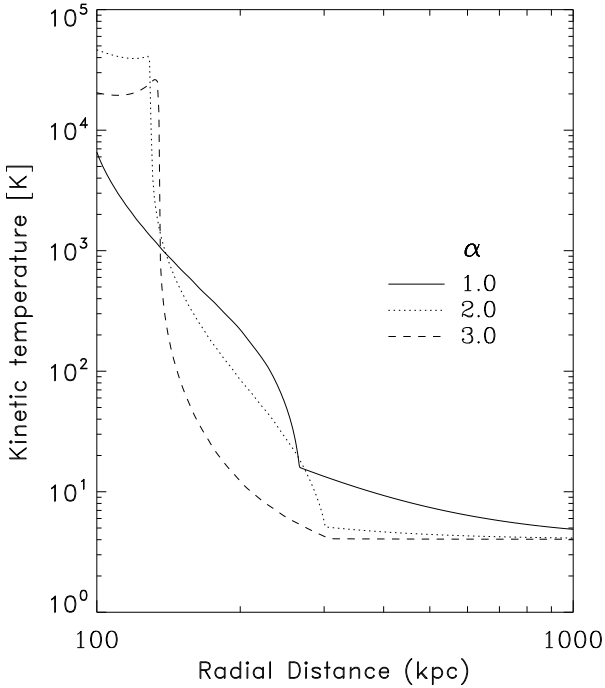


Figure 11. Temperature around a $10^6 M_\odot$ black hole is plotted for three different spectral indices at $z=20$. We see the decrease in heating with steeper indices. Decrease of low energy photons being the cause of this behaviour.

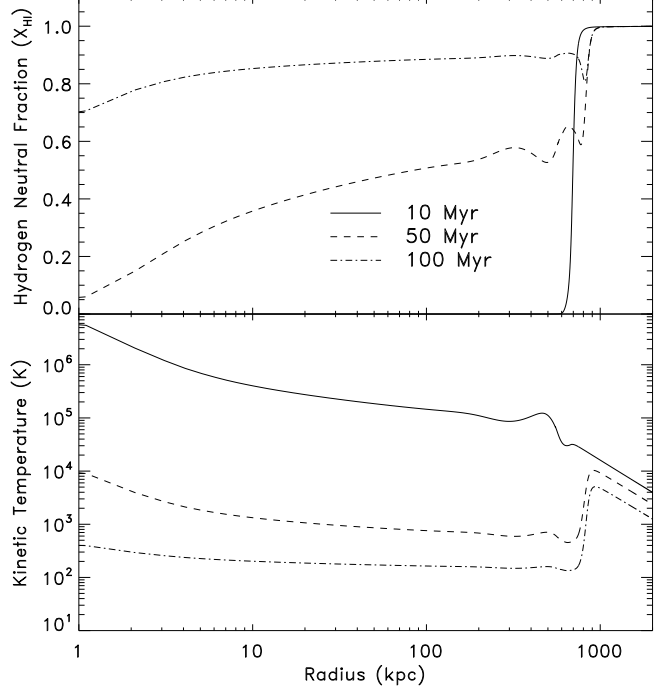


Figure 12. Figure shows the neutral fraction (top panel) and kinetic temperature (bottom panel) for three different times after the quasar was switched on as indicated in the figure. The quasar is at redshift $z = 10$ and hosts a $1000 M_\odot$ black hole in the centre, which is switched on for the first 10 Myr and switched off since then.

heating is relatively less at higher densities because most of the photons are absorbed to ionize and the dominant cooling terms, e.g., like the Hubble cooling, are enhanced at higher densities.

5 APPLICATION TO STELLAR (BLACKBODY) SOURCES

Unlike quasars and miniquasars that have a power-law distribution of energy in their spectrum, the stars approximately behave as a blackbody of a given temperature. This blackbody nature of the source leaves different signatures in the manner the IGM is heated and ionized. Given the weak dependence of the star's temperature on its mass (see Schaerer (2002)), we fix the blackbody temperature of the stars to 5×10^4 K and mass ranges between 10 and $1000 M_\odot$. The total luminosity for a given stellar mass is calculated from table 3 of Schaerer (2002). The other difference in case of stars is the density profile in which it is embedded. We assumed a density profile of the form;

$$\begin{aligned} \rho(r) &= 3.2 \times (91.5 \text{ pc}/r)^2 [\text{cm}^{-3}] \quad (r \leq r_c) \\ &= n_i(0) \times (1+z)^3 [\text{cm}^{-3}] \quad (r > r_c), \end{aligned} \quad (21)$$

where $n_i(0)$, is the density of the hydrogen or helium at redshift 0 and r_c is the radius at which the density profile falls to that of the mean IGM.

Depending on the temperature, the spectrum used above for the stars peaks in between $\approx 20 \text{ eV}$ to $\approx 24 \text{ eV}$ (for 10^5 K). What is expected in the case of stars of the same power output as a quasar are bigger ionized bubbles and less heating. Simply because, after

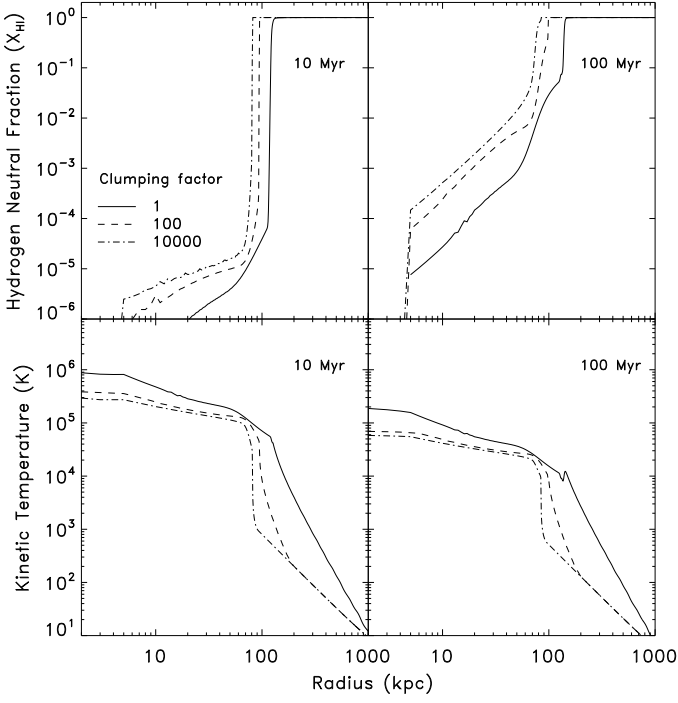


Figure 13. Figure shows the neutral fraction (top panels) and kinetic temperature (bottom panels) for three different clumping factors at 10 Myr and 100 Myr as indicated. The quasar is active at redshift $z = 20$ and hosts a $1000 M_{\odot}$ black hole in the centre, which is switched on for the first 10 Myr and switched off since then.

the peak, which is around the ionization threshold of hydrogen and helium, we have an exponential cutoff towards higher frequencies.

After modifying the spectrum and the underlying density profile, we basically did the same exercise as for the miniqsos. Some of the results are plotted in the following Figures. The hydrogen neutral fraction is plotted in figure 14 as a function of distance from the source with an effective blackbody temperature of 50000 K. Note that unlike the miniqsos case the x-axis here runs only up to 100 kpc physical. This is because the most massive stars considered here, i.e., $1000 M_{\odot}$, has a luminosity of a $10 M_{\odot}$ black hole shining at the Eddington rate (Schaerer 2002).

A similar case of lower ionized helium is seen in Figure 15. Observe again that the helium front is leading. Because for high temperature stars the blackbody peaks at higher energies closer to the ionization threshold of helium.

Figure 16 shows kinetic temperature as a function of radial distance for Population III stars with masses of $10 - 1000 M_{\odot}$. Notice that even though the maximum temperatures reached are comparable to that of the miniqso, the extent and shape of the profile are distinctly different. There is a much sharper edge to the heating attributed to the fact there are not many high energy (100 eV and above) photons and hence the mean free path of most photons is lower.

6 OBSERVATIONAL EFFECTS

There are many indications of an epoch of reionization in the Universe. But observations currently are only able to provide us with either an integral limit (CMB data) or a lower limit (Gunn-Peterson

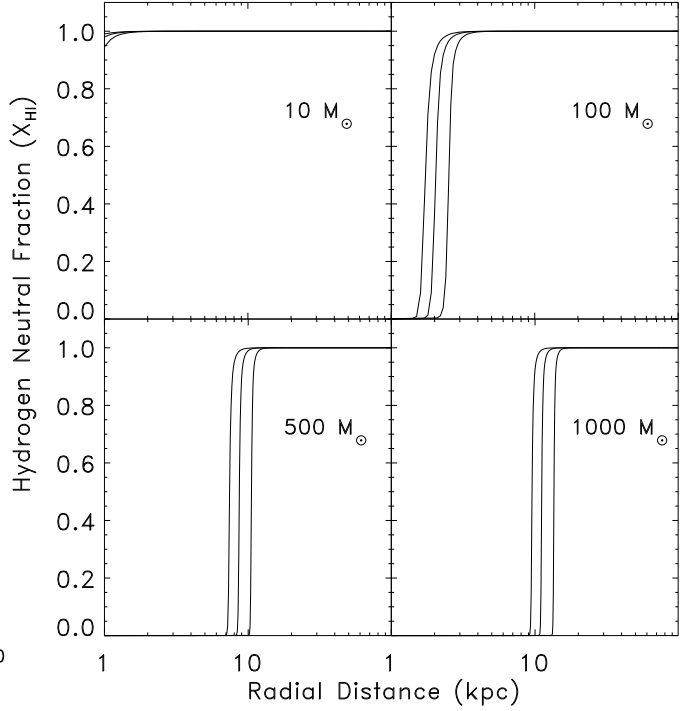


Figure 14. The neutral hydrogen fraction as a function of distance from the centre of the blackbody with an effective temperature of 50000K and masses $10, 100, 500, 1000 M_{\odot}$ (top-left to bottom right panel) at a redshift $z = 20$. The three lines corresponds to the I-front position after 2, 3 and 5 Myr of evolution.

troughs) on the redshift of reionization. Direct detection and study of this epoch currently rests on the future 21 cm radio observations and temperature fluctuations because of the SZ effect (detectable by PLANCK⁸) and probable direct observations of very high redshift Population III stars by JWST⁹.

In this paper we will concentrate on the feasibility of radio observations on the detection and mapping of the epoch of reionization. A point to note is that from here on in the case of miniqsos we only use the low energy case because the heating would be less exaggerated and probably closer to reality.

6.1 Spin Temperature

The spin temperature T_s couples to either the CMB temperature T_{CMB} or to the kinetic temperature T_e , in the absence of other radio sources (Field 1958; Kuhlen, Madau, & Montgomery 2006). Thus T_s can be written as a weighted sum between T_e and T_{CMB} ,

$$T_s = \frac{T_{\star} + T_{\text{CMB}} + y_{\text{col}}T_e + y_{\alpha}T_e}{1 + y_{\text{col}} + y_{\alpha}}. \quad (22)$$

$T_{\star} = h\nu_{21\text{cm}}/k = 0.0681 \text{ K}$, y_{col} and y_{α} determines the efficiency of collisional and Ly α coupling and is given by,

$$y_{\text{col}} = \frac{T_{\star}}{A_{10}T_e}(C_H + C_e + C_p) \quad (23)$$

⁸ <http://www.rssd.esa.int/index.php?project=PLANCK>

⁹ <http://www.jwst.nasa.gov/>

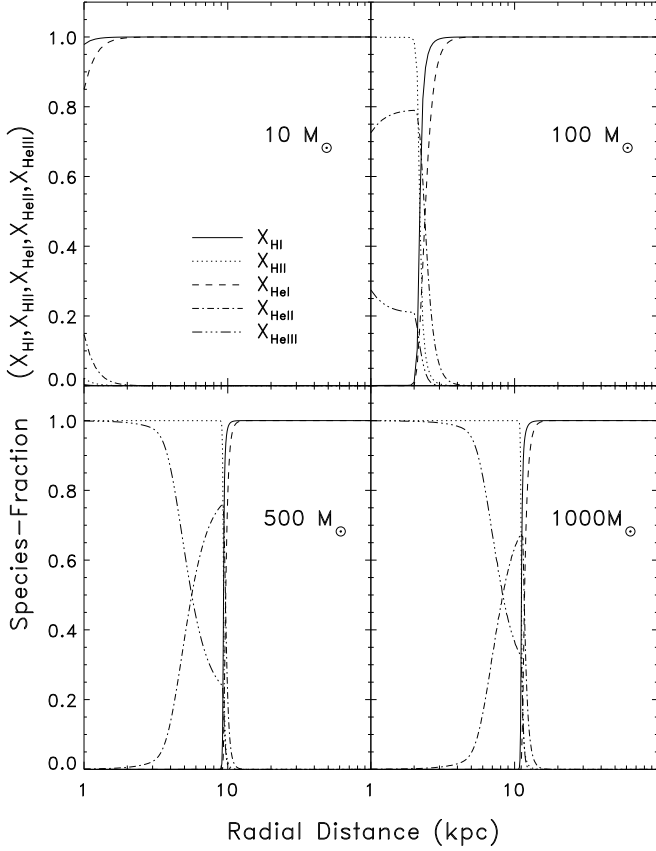


Figure 15. Fraction of various species ($x_{\text{HI}}, x_{\text{HII}}, x_{\text{HeI}}, x_{\text{HeII}}, x_{\text{HeIII}}$) for the shown star masses.

where, $A_{10} = 2.85 \times 10^{-15} \text{ s}^{-1}$ is the spontaneous emission rate or the Einstein A-coefficient and C_H , C_e , and C_p are the de-excitation rates of the triplet due to collisions with neutral atoms, electrons, and protons, respectively. The empirical fits for these coefficients are identical to those used by Kuhlen, Madau, & Montgomery (2006), which is a combination of results published in Zygelman (2005), Allison & Dalgarno (1969), Liszt (2001) and Smith (1966). And the $\text{Ly}\alpha$ coupling coefficient (discussed in section §6.2);

$$y_\alpha = \frac{16\pi^2 T_* e^2 f_{12} J_o}{27 A_{10} T_e m_e c} \quad (24)$$

Here, J_o is the $\text{Ly}\alpha$ flux density. For the miniquasars high energy photons $\text{Ly}\alpha$ coupling is mainly caused by collisional excitation due to secondary electrons (Chuzhoy, Alvarez, & Shapiro 2006). This process is accounted for by the following integral,

$$J_o(r) = \frac{\phi_\alpha c}{4\pi H(z) \nu_\alpha n_{\text{HI}}(r)} \int_{E_o}^{\infty} \sigma(E) N(E; r) dE, \quad (25)$$

where $f_{12} = 0.416$ is the oscillator strength of the $\text{Ly}\alpha$ transition, e & m_e are the electron's charge and mass, respectively. ϕ_α is the fraction of the absorbed photon energy that goes into excitation (Shull & van Steenberg 1985). The contribution of this term is important close to the miniquasar.

Note that in reality, we have to include the frequency dependence of the $\text{Ly}\alpha$ cross section, the background continuum $\text{Ly}\alpha$ photons and scattering (Chen & Miralda-Escude 2006). But since

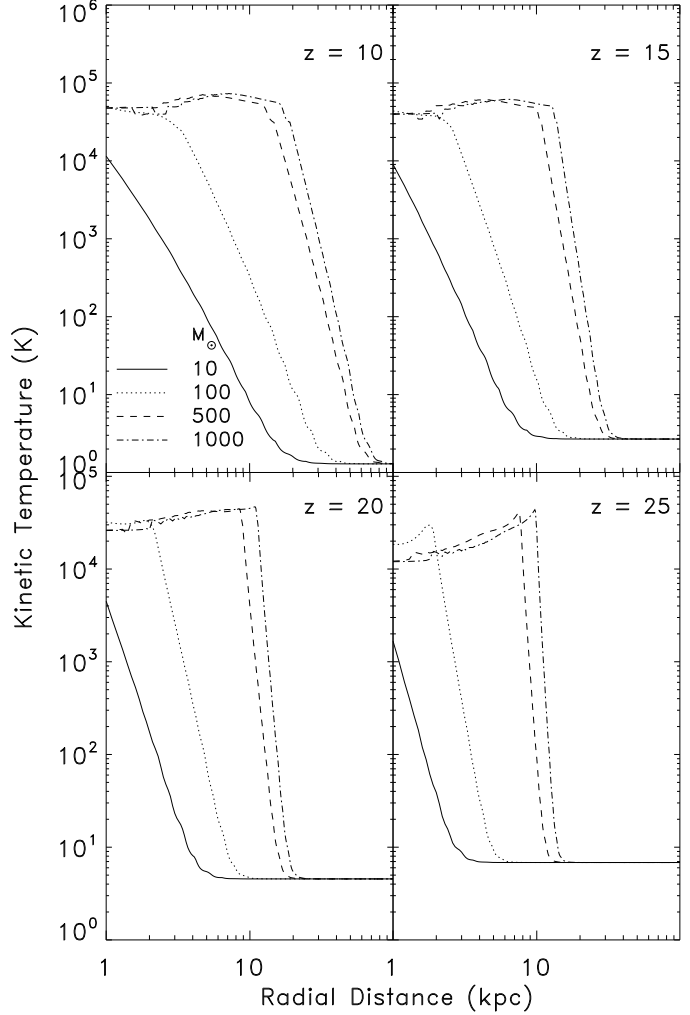


Figure 16. Radial profile of Kinetic temperature T_e for stars with masses 10, 100, 500 and $1000 M_\odot$ at 4 different redshift $z = 10, 15, 20, 25$ (top-left to bottom right panel) are shown.

we are dealing only with “injected” photons at the $\text{Ly}\alpha$ frequency we only include the cross section at the line centre with thermal broadening.

Results of the spin temperature for a black hole of mass $10^4 M_\odot$ is shown in Figure 17 for 4 different redshifts. For reasons discussed in the next section the spin temperature follows the kinetic temperature for considerable distance away from the source and then follows the background CMB temperature at larger distances.

The spin temperature for the case of a $1000 M_\odot$ at 4 different redshifts is shown in Figure 18. The spin temperature, for the case of stars, is assumed to follow the kinetic temperature for a distance of ‘ct’, although this might be an over estimate because there is a sharp cut-off towards red ward of the black body peak reducing the number of $\text{Ly}\alpha$ produced by the source itself. But with a combination of the background $\text{Ly}\alpha$, it might be possible to couple the spin temperature to the kinetic temperature.

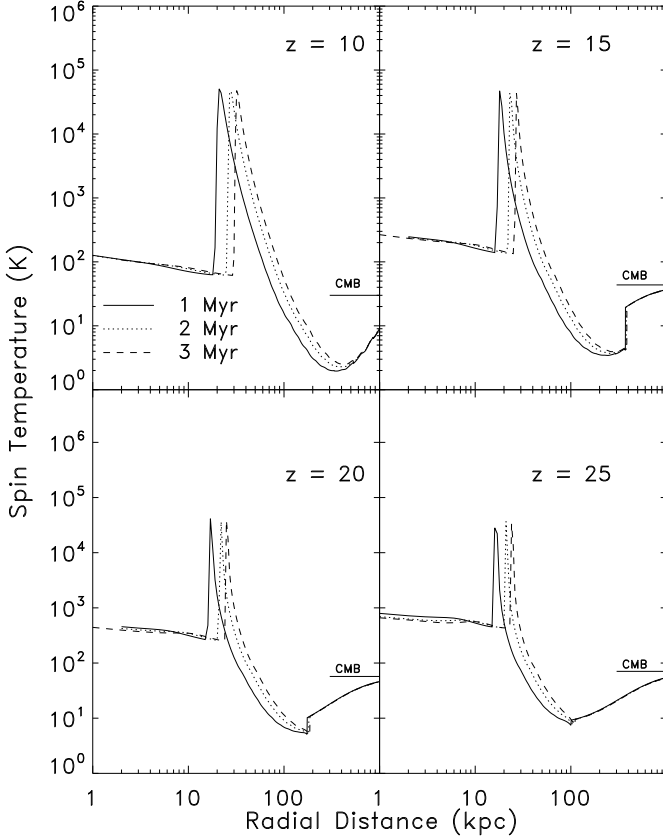


Figure 17. Radial profile of spin temperature T_s for a black hole with mass $10^4 M_\odot$ at 4 different redshift $z = 10, 15, 20, 25$ (top-left to bottom right panel) for 1, 2 and 3 Myrs of evolution after the source was switched on. Note that the curves identical to that of the kinetic temperature in Fig. 9 except the spin temperature climbs back to T_{CMB} after about 1000 kpc corresponding to the photon propagation distance in 3 Myrs. These miniquasars include the low energy photons.

6.2 Lyman α coupling

Ly α coupling is known to be the most efficient mechanism to couple the kinetic temperature to the spin temperature, at least in the mean IGM. Collisional coupling only becomes important in overdense regions with gas over-densities $\delta \geq 20[(1+z)/10]^{-2}$ (Iliev et al. 2003; Furlanetto & Loeb 2002). Since we are interested in studying brightness temperature fluctuation relatively far away from the source, the dominant mode of coupling for our purposes is Ly α pumping.

There are a number of ways to generate Ly α photons. 1) The source itself produces continuum photons between Ly α and Ly β , which is then redshifted at a distance from the source to Ly α . 2) Photons above the Ly β produced by the source pumps the electrons to higher levels which then cascade back to produce Ly α . 3) Secondary electrons can deposit a part of their energy towards exciting the hydrogen atom (Shull & van Steenberg 1985). 4) If we are looking at sources at lower redshifts (< 20) then there is enough background Ly α from “first stars” Ciardi & Madau (2003).

The Ly α flux density estimated in equation 25 is efficient to couple the spin temperature to the kinetic temperature. The

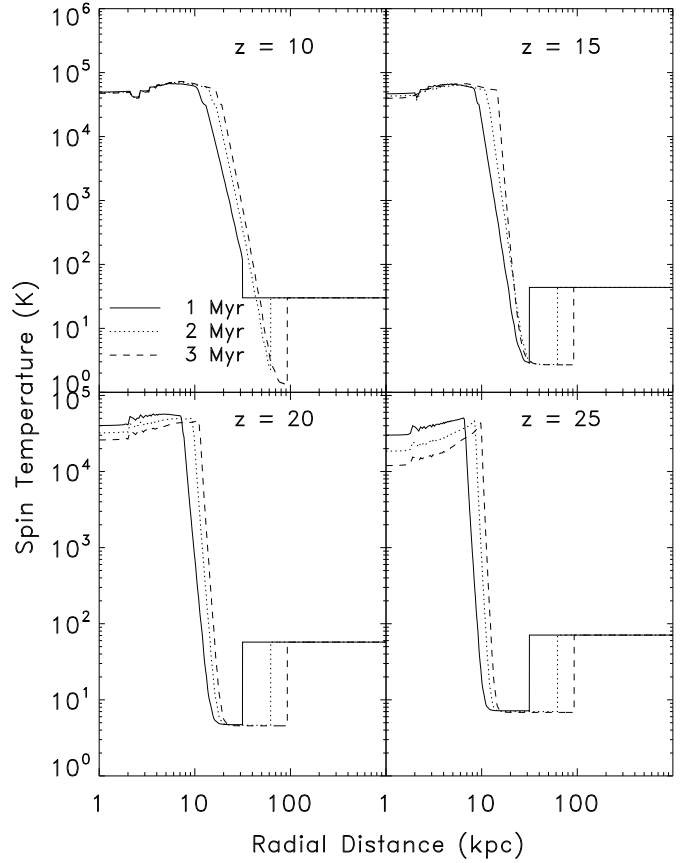


Figure 18. Radial profile of spin temperature T_s for stars with a mass $1000 M_\odot$ at 4 different redshifts $z = 10, 15, 20, 25$ (top-left to bottom right panel) are shown. The temperature of the star is assumed to be 50000K.

Wouthuysen-Field effect¹⁰ is efficient within the photon propagation (or light travel) time if these photons come directly from the source within the energy range of ionization (13.6 eV) and Ly α (10.4 eV). But, even in the case when the source does not produce Ly α photons, the secondary excitations are efficient enough to couple T_s with T_e to a large distance away from the source as seen from Figure 17. But at lower redshifts the background Ly α flux would be large enough to de-couple T_s from T_{CMB} much further away from the source (Ciardi & Madau 2003). In the case of stars we do not expect a major influence of the secondary electrons on ionizations or excitations. Thus we assume that the Ly α flux originates from the source/background. Hence, we allow the spin temperature to follow the kinetic temperature to the light travel distance “ct”.

6.3 Brightness temperature

Under the “low-frequency” or Rayleigh-Jeans’ approximation, the equation for blackbody radiation reduces to,

$$I(\nu) = \frac{2\nu^2}{c^2} kT_b. \quad (26)$$

¹⁰ The Wouthuysen-Field mechanism basically is the mixing of the hyper-fine state in neutral hydrogen in its ground state via intermediate transitions to the 2p and above states (Wouthuysen 1952; Field 1958)

Where $I(\nu)$ is the intensity of radiation at frequency ν , k the Boltzmann constant, c the speed of light and T_b is the brightness temperature. And in radio astronomy this limit is applicable. Brightness temperature can be measured differentially as a deviation from the background CMB temperature T_{CMB} (Field 1958; Ciardi & Madau 2003) as,

$$\delta T_b = 26 \text{ mK} (1 + \delta) x_{\text{HI}} \left(1 - \frac{T_{\text{CMB}}}{T_s}\right) \left(\frac{\Omega h^2}{0.02}\right) \left[\left(\frac{1+z}{10}\right) \left(\frac{0.3}{\Omega_m}\right)\right]^{1/2}. \quad (27)$$

Where x_{HI} is the neutral hydrogen fraction (see Fig 4), δ is the overdensity of hydrogen (atoms and ions) and T_s is the spin temperature (Ref Fig 17). So given the cosmology and the redshift, which translates to a frequency of observation, the brightness temperature in equation 27 basically reflects the source characteristics in two ways. One that enters through the neutral fraction x_{HI} , defined by the ionizing capabilities of the source and another through the spin temperature T_s which in effect reflects kinetic temperature dictated by the heating capacity of the source. Thus, we hope that a 3D tomography could not only reveal a statistical signal, the power spectrum and the large scale structure of the epoch reionization but also give us clues on the nature of these first sources.

As an example, we can consider the HE and the LE case. Although the heating pattern and extent in both these cases are similar (see Figure 8 & 9), the ionization profiles are indeed different (see Figure 4 & 5). This according to equation 27 will be reflected in the brightness temperature.

Figure 19 shows the radial profile for the expected brightness temperature for the same case as discussed in the context of the spin temperature above. For all cases there is almost a sudden jump in the brightness temperature. This is due to the sharp transition in the neutral fraction (Ref Fig 4).

The ionized fraction (Fig.14) and spin temperature profile (Fig.18) is also reflected in the brightness temperature in the case of stars as in Figure 20. The maximum of the brightness temperature has a typical value between 20 and 30 mK for all redshifts but the negative wing spans different ranges depending on the redshift.

An interesting observation is that the maximum value of T_b remains the same throughout the mass range. The reason being that in all cases T_s is driven far away from T_{CMB} , such that the term $\left(1 - \frac{T_{\text{CMB}}}{T_s}\right)$ in equation 27 approximates to unity thus removing the dependence of T_b on T_s . As a consequence of this, we also see that the brightness temperature does not change considerably during the dormant period of the quasar. Figure 13 shows ionized fraction and temperature profile after the quasar has been switched off. But the ionized fraction is still low ($\approx 10^{-4}$) in the inner regions of the I-front, and the temperature is considerably high. Thus, the brightness temperature profile essentially remains the same.

Zaroubi & Silk (2005) have found that for power-law sources like minisquos the brightness temperature has an extended feature in the transition from the ionized to neutral IGM. This feature has the same order of magnitude of the one found here (see Figure 19). However, it should be noted that the origin of this feature in both cases is completely different. While in Zaroubi & Silk (2005) the extended feature is produced by the ionization-recombination balance of high energy photons, here the origin of this feature is in the heating not ionization pattern around these sources, also caused by high energy photons. As Figure 4 shows the neutral fraction of hydrogen changes abruptly at the I-front location, namely, we here

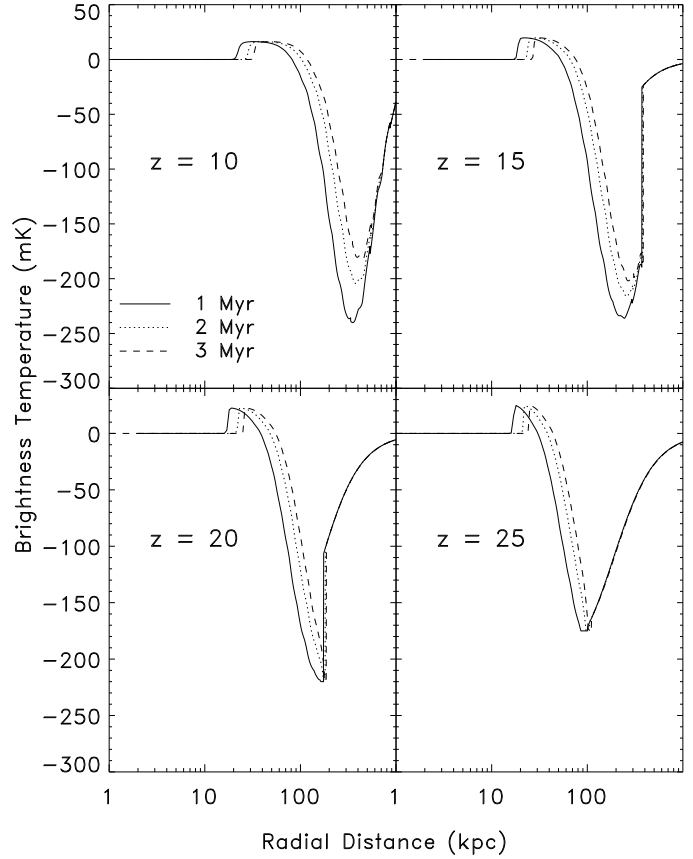


Figure 19. Radial profile of brightness temperature dT_b for the same black hole model as in fig.17.

show that the equilibrium assumption of Zaroubi & Silk (2005) is never attained during the minisqo lifetime.

6.4 Observability with future telescopes

As mentioned before, there are several interferometric radio telescopes underway to measure the 21cm signature of the EoR. It would be of interest to investigate into the possibility measuring directly the topology of the 21cm through the brightness temperature. This of course depends on the angular resolution, that measures the topology on the sky and the frequency resolution that will provide the depth information. We look into these aspects in the context of LOFAR and SKA measuring the 21cm signal from redshift 10. LOFAR¹¹ will have an angular resolution of about 3-5 arcmin and a spectral resolution of 1MHz. This would correspond to a physical size on the sky of ≈ 1.4 Mpc and ≈ 5 Mpc in depth. On the other hand SKA with an angular resolution of about 1 arcmin (Carilli & Rawlings 2004) would correspond to $\approx .5$ Mpc on the sky. The spectral resolution for the EoR experiment would more or less remain the same to beat other noise effects. In the light of these rough estimates we realize that it would be unlikely for LOFAR to see individual sources, although once the “bubbles” start merging the sizes may become comparable. But SKA, in principle should

¹¹ www.astro.rug.nl/LofarEoR

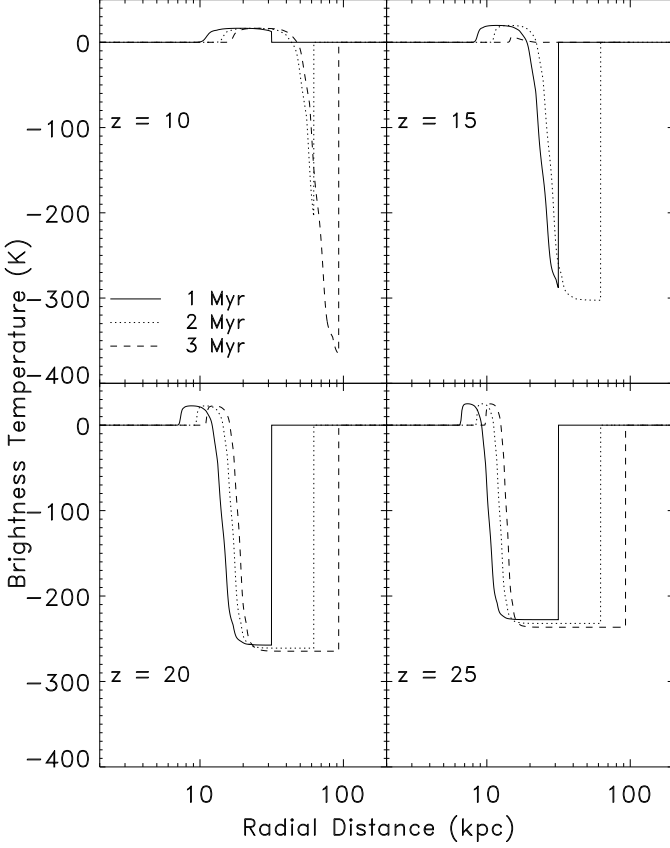


Figure 20. Brightness temperature calculated for the spin temperatures of the star shown in fig.18. Assumption has been made that the spin temperature remains coupled to the kinetic temperature for a radius “ ct ”.

be able to resolve at least the relatively big bubbles of the order of 100 of kpc easily.

7 SUNYAEV-ZE'LDOVICH EFFECT

Possibilities of observing the thermal and kinetic Sunyaev-Ze'dovich (SZ) effect during the epoch of reionization had been first investigated by Aghanim et al. (1996) and more recently by Iliev et al. (2007). A hot ball of ionized gas around first stars or miniqsos resembles the classic case of clusters at lower redshifts in which the SZ effect is observed today. Thus looking for signs of reionization through the SZ effect is an obvious next step. A spin-off of the simulations of the ionization and heating of the IGM by miniqsos is the estimation of their contribution to the Sunyaev-Ze'dovich (SZ) effect. Both, the thermal and the kinetic SZ-effects have been considered.

For these simulations we start at z of 20 with two seed black hole masses, 10^3 and $10^4 M_\odot$. These two cases are explored in order to reach, through accretion, masses of quasars observed at redshift 6 by the SDSS. The black holes are allowed to grow in time according the following equation.

$$M(t) = M_0 \exp(f_{duty} t/t_E), \quad (28)$$

where $M(t)$ is the mass of the black hole at time ' t ', f_{duty} the duty cycle of the black hole and t_E the time scale of growth which

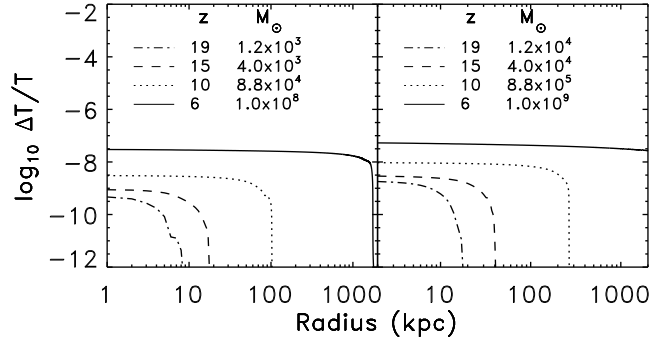


Figure 21. Thermal Sunyaev-Ze'dovich effect: Radial profile of temperature fluctuation $\frac{\Delta T}{T}$ for seed black hole masses $10^3 M_\odot$ and $10^4 M_\odot$ beginning at redshift $z = 20$ are shown. The different lines corresponds to particular redshifts as indicated in figure. Corresponding mass according to equation 28 is shown.

is around $41 \times (\epsilon_{rad}/0.1)$ Myrs. The radiation efficiency of ϵ_{rad} was set to 0.05 (Loeb 2006). We assumed a duty cycle of 30%.

First objects are formed in regions that are overdense with respect to the IGM. Thus, we ran the above simulations for a density that is ten times the mean IGM density at that epoch.

Thermal SZ-effect:

Hot electrons transfer energy to the CMB photons via inverse Compton scattering, redistributing the photons in the spectrum generally towards higher energy (Sunyaev & Ze'dovich 1972, 1980). The temperature fluctuation is thus given by;

$$\frac{\Delta T}{T} = -2 \frac{k_b \sigma_T}{m_e c^2} \int_0^R T_e(t; l) n_e(t; l) dl \quad (29)$$

where T_e , m_e and n_e are the electron's temperature, rest mass and density, respectively. σ_T is the Thomson cross section and R is the radius of the ionized region. T_e and n_e are functions of the radius and time after the quasar was switched on. All parameters required to compute equation (29) have been obtained from the simulation.

The SZ-effect is the line of sight integral of the electron pressure. In order to estimate the effect we considered the profiles of the temperature and the ionized fraction to be spherically symmetric and then projected the effect onto the plane of the sky. Figure 21 shows the temperature fluctuations resulting from the black hole model mentioned above. Results are plotted for different redshifts along with their corresponding masses, down to a redshift of 6. All of them end at redshift 6 with masses comparable to the black hole masses estimated for the SDSS high redshift quasars (Fan et al. 2003, 2006). Massive miniqsos can cause temperature fluctuations at high redshifts on the order of 10^{-7} K.

Kinetic SZ-effect

Apart from the thermal SZ-effect, there is also the possibility of observing these large ionized bubbles through the kinetic SZ-effect. Peculiar Motion of an ionized bubble with respect to the background leads to an additional change of radiation temperature in its direction, because of the finite optical depth associated with the bubble (Sunyaev & Ze'dovich 1972). The average anisotropy associated with an ionized bubble is given by,

$$\frac{\Delta T}{T} = \frac{2}{3} \frac{v_r}{c} \int_0^R 2\sigma_T n_e(t; l) dl \quad (30)$$

where v_r is the radial component of the peculiar velocity of the ionized bubble. The electron density $n_e(t; l)$ is given by the simulation

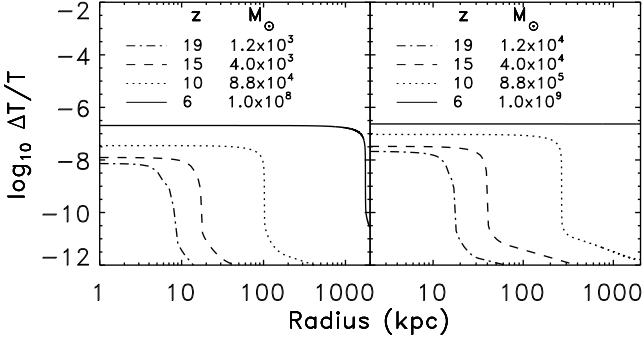


Figure 22. *Kinetic Sunyaev-Ze’ldovich effect:* Radial profile of temperature fluctuation $\Delta T/T$ for the same model as in figure 21

and the radial component of the velocity dispersion is computed in the limit of linear theory and is given by,

$$v_r(z) = v_r(0)(1+z)^{-1/2}, \quad (31)$$

where $v_r(0)$ is velocity dispersion at redshift zero fixed at 600 km/s.

The temperature fluctuation as a result of the kinetic SZ effect (eq. 30) is shown as a function of the radial distance from the source in figure 22. Again, as for the previous case, we assumed spherical symmetry. The kinetic SZ-effect is in fact larger in magnitude than thermal SZ-effect, making it easily visible on the temperature maps of PLANCK. Therefore, if the sizes and temperatures of these early ionized bubbles are of the same order of magnitude predicted here, then the SZ-effect is an important and independent probe of the impact of early sources on the reionization history that could be observed in the near future.

8 SUMMARY AND CONCLUSIONS

In this paper a 1-D radiative transfer code has been developed in order to study in detail the influences of primordial black holes and Pop III stars on their surrounding environment. We have shown, in agreement with many other authors, that black holes and/or Pop III stars have the potential to have been the primary source of ionization. Although the ionized regions around typical black holes and Pop III stars is not shown to be convincingly different modulo the resolution of the telescopes like LOFAR, the heating around these two sources do have a significantly different profile. This in turn is reflected in the spin temperature of the system, which then directly translates into the brightness temperature measured by the radio telescope.

Spin temperatures are coupled to the kinetic temperature either through collisions or through $\text{Ly}\alpha$ pumping. Strengths of these coupling terms are studied as a function of the radial distance from the source. $\text{Ly}\alpha$ photons do couple the spin temperature efficiently to the kinetic temperature hence making the brightness temperature insensitive to the background CMB, at least for a substantial distance ($\approx 2 - 3 \text{ Mpc}$) away from the source.

Recombination timescales are orders of magnitude lower than that of ionization. Therefore, an HII bubble remains ionized for a long period after the source of radiation has been switched off. Also the temperature remains largely unchanged for a significant fraction of Hubble time since cooling processes typically involve

two body interaction that increase the timescales involved. Interestingly for miniquasars, a marginal increase in the ionized bubble after the switching off of the central ionizing source is observed. Collisional ionizations are the dominant cause of this phenomenon which is therefore relatively less in stars because of the lack of high energy X-ray photons which heats up the environment significantly hence boosting the collisional ionizations.

For miniquasars with a hard spectrum that lacks the UV part of the spectrum we observe an excess of HI fraction as a function of radius just before the main ionization front. This is interpreted as a result of the interplay between the increase of HeII and decrease of HeIII, which increase the HI recombination rate, on the one hand and the decrease in the photon flux as a function of radius on the other. This interpretation is supported by the weakening of the HI excess feature as a function of black hole mass. This phenomenon is not observed in miniquasars with spectrum that has UV photons, which is due to the ionization efficiency of these photons.

The results of the IGM heating around miniquasars have also been compared to the analytical approach of Zaroubi et al. (2007). Results shown in Figure A1 demonstrate that the analytical solutions, while in agreement to within an order of magnitude, underestimate the kinetic temperature away from the centre by roughly a factor of up to 5. The difference in the results is due to the helium species cross-sections are not being fully accounted for in the analytical approach. In fact, in order for the heating to be accurately calculated one needs an exact knowledge of the abundance of each of the hydrogen and helium species averaged over their evolution history until the point in time in which one is interested and such detailed knowledge could not be obtained with the analytical approach.

Also, the thermal and kinetic Sunyaev-Ze’ldovich effects around these quasars were studied. Two cases are considered in which mass growth of the black hole is incorporated such that it winds up with 10^8 and $10^9 M_\odot$ black holes at redshifts close to six. The estimated values for the temperature fluctuations are within the sensitivities of the future mission like PLANCK.

We conclude that the brightness temperature which in turn reflects the underlying ionization and heating around a source is sensitive to many factors. The spectral energy distribution of the source, range of energies spanned by the photons of these sources, their clustering properties, the photon escape fraction, the redshifts at which the sources turn-on, their lifetimes, and many other complex feedback mechanisms, to name a few that will influence the brightness temperature, which is the observable we are after. Thus, in order to span this large parameter space of possibilities a 1D radiative transfer code is very useful.

An important next step for the radiative transfer code described here is to include line emissions and absorptions, especially that of the $\text{Ly}\alpha$ line, in the radiative transfer equations. We will also incorporate the rate equation for molecular hydrogen and its various states.

Finally, in the near future we plan to incorporate the results of this study into the output of N-body simulations. Such an approach will allow us to produce quick 21 cm maps of the EoR, which then will be used in conjunction with the simulations of galactic and extra-galactic foregrounds, ionospheric models and LOFAR specific instrument responses to generate “dirty-maps” of the EoR.

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REFERENCES

- Abel T., Wise J. H., Bryan G. L., 2007, *ApJ*, 659, L87
- Aghanim N., Desert F. X., Puget J. L., Gispert R., 1996, *A&A*, 311, 1
- Allison A. C., Dalgarno A., 1969, *ApJ*, 158, 423
- Barkana R., Loeb A., 2001, *PhR*, 349, 125
- Begelman M. C., Volonteri M., Rees M. J., 2006, *MNRAS*, 370, 289
- Benson A. J., Sugiyama N., Nusser A., Lacey C. G., 2006, *MNRAS*, 369, 1055
- Bharadwaj S., Ali S. S., 2005, *MNRAS*, 356, 1519
- Bromm V., Kudritzki R. P., Loeb A., 2001, *ApJ*, 552, 464
- Carilli C. L., Gnedin N., Furlanetto S., Owen F., 2004, *NewAR*, 48, 1053
- Carilli C., Rawlings S., 2004, *astro*, arXiv:astro-ph/0409274
- Chen X., Miralda-Escude J., 2006, *astro*, arXiv:astro-ph/0605439
- Chuzhoy L., Alvarez M. A., Shapiro P. R., 2006, *ApJ*, 648, L1
- Ciardi B., Ferrara A., White S. D. M., 2003, *MNRAS*, 344, L7
- Ciardi B., Madau P., 2003, *ApJ*, 596, 1
- Dijkstra M., Haiman Z., Loeb A., 2004, *ApJ*, 613, 646
- Dijkstra M., Haiman Z., Rees M. J., Weinberg D. H., 2004, *ApJ*, 601, 666
- Dopita M. A., Sutherland R. S., 2003, *adu..book*, Elvis M., et al., 1994, *ApJS*, 95, 1
- Fan X. et al., 2003, *ApJ*, 125, 1649
- Fan X., et al., 2006, *AJ*, 131, 1203
- Field G. B., 1958 *Proc I.R.E.*, 46, 240
- Fukugita M., Kawasaki M., 1994, *MNRAS*, 269, 563
- Furlanetto S. R., Loeb A., 2002, *ApJ*, 579, 1
- Furlanetto S. R., Zaldarriaga M., Hernquist L., 2004, *ApJ*, 613, 16
- Furlanetto S. R., Zaldarriaga M., Hernquist L., 2004, *ApJ*, 613, 1
- Hogan C. J., Rees M. J., 1979, *MNRAS*, 188, 791
- Iliev I. T., et al., 2006, *MNRAS*, 371, 1057
- Iliev I. T., Pen U.-L., Bond J. R., Mellema G., Shapiro P. R., 2007, *ApJ*, 660, 933
- Iliev I. T., Scannapieco E., Martel H., Shapiro P. R., 2003, *MNRAS*, 341, 81
- Jones B. J., Wyse R. F. G., 1985, *A&A*, 149, 144
- Kitayama T., Yoshida N., Susa H., Umemura M., 2004, *ApJ*, 613, 631
- Kuhlen M., Madau P., Montgomery R., 2006, *ApJ*, 637, L1
- Kuhlen M., Madau P., 2005, *MNRAS*, 363, 1069
- Laor A., Fiore F., Elvis M., Wilkes B. J., McDowell J. C., 1997, *ApJ*, 477, 93
- Liszt H., 2001, *A&A*, 371, 698
- Loeb A., 2006, *astro*, arXiv:astro-ph/0603360
- Madau P., Efstathiou G., 1999, *ApJ*, 517, L9
- Madau P., Meiksin A., Rees M. J., 1997, *ApJ*, 475, 429
- Mellema G., Iliev I. T., Alvarez M. A., Shapiro P. R., 2006, *NewA*, 11, 374
- Nusser A., 2005, *MNRAS*, 359, 183
- Press W. H., Teukolsky S. A., Vetterling W. T., Flannery B. P., 1992, *Numerical Recipes in C. The Art of Scientific Computing*, Cambridge University Press, Cambridge.
- Ricotti, M., Ostriker, J. P., 2004a, *MNRAS*, 350, 539.
- Ricotti, M., Ostriker, J. P., 2004b, *MNRAS*, 352, 547
- Rhook K. J., Haehnelt M. G., 2006, *MNRAS*, 373, 623
- Sazonov S. Y., Ostriker J. P., Sunyaev R. A., 2004, *MNRAS*, 347, 144
- Schaerer D., 2002, *A&A*, 382, 28
- Scott D., Rees M. J., 1990, *MNRAS*, 247, 510
- Shapiro P. R., Giroux M. L., 1987, *ApJ*, 321, L107
- Shaver P. A., Windhorst R. A., Madau P., de Bruyn A. G., 1999, *A&A*, 345, 380
- Smith F. J., 1966, *P&SS*, 14, 929
- Spaans M., Silk J., 2006, *ApJ*, 652, 902
- Spergel D. N., et al., 2007, *ApJS*, 170, 37
- Shull J. M., van Steenberg M. E., 1985, *ApJ*, 298, 268
- Sunyaev R. A., Ze'ldovich I. B., 1980, *MNRAS*, 190, 413
- Sunyaev R. A., Zeldovich I. B., 1975, *MNRAS*, 171, 375
- Sunyaev R. A., Ze'ldovich Y. B., 1972, *CoASP*, 4, 173
- Tozzi P., Madau P., Meiksin A., Rees M. J., 2000, *ApJ*, 528, 597
- Vanden Berk D. E., et al., 2001, *AJ*, 122, 549
- Verner, D. A., Ferland, G. J., Korista, K. T., & Yakovlev, D. G. 1996, *ApJ*, 465, 487
- Vignali C., Brandt W. N., Schneider D. P., 2003, *AJ*, 125, 433
- Volonteri M., Lodato G., Natarajan P., 2007, *arXiv*, 709, arXiv:0709.0529
- Whalen D., Abel T., Norman M. L., 2004, *ApJ*, 610, 14
- Wouthuysen S. A., 1952, *AJ*, 57, 31
- Wyithe J. S. B., Loeb A., 2004, *ApJ*, 610, 117
- Wyithe S., Loeb A., 2003, *astro*, arXiv:astro-ph/0302297
- Wyithe J. S. B., Loeb A., 2002, *ApJ*, 581, 886
- Zaldarriaga M., Furlanetto S. R., Hernquist L., 2004, *ApJ*, 608, 622
- Zaroubi S., Thomas R. M., Sugiyama N., Silk J., 2007, *MNRAS*, 375, 1269
- Zaroubi S., Silk J., 2005, *MNRAS*, 360, L64
- Ze'ldovich Y. B., Sunyaev R. A., 1969, *Ap&SS*, 4, 301
- Zygelman B., 2005, *ApJ*, 622, 1356

APPENDIX A: ANALYTICAL APPROXIMATION

A number of papers have outlined analytical approximations for the ionized fraction and heating of the IGM by miniquasars (cf., Madau, Meiksin, & Rees (1997); Zaroubi et al. (2007)). In order to test the validity of these analytical solutions, we compare such a solution with the RT simulations for 100 and $10^4 M_\odot$ black hole masses at z of 20 and 10 and with a lifetime of 3 and 10 Myr. Here we follow the analytical equations of Zaroubi et al. (2007) who calculate the ionization species by solving the following ionization-recombination equilibrium equation;

$$\alpha_{HI}^{(2)} n_H^2 (1 - x_{HI})^2 = \Gamma(E; r) n_H x_{HI} \left(1 + \frac{\sigma_{He} n_{He}}{\sigma_H n_H} \right). \quad (A1)$$

where $\Gamma(E; r)$ is the ionization rate per hydrogen atom for a given photon energy at distance r from the source. Γ is calculated as a function of r ;

$$\Gamma(E; r) = \int_{E_0}^{\infty} \sigma(E) \mathcal{N}(E; r) \frac{dE}{E}. \quad (A2)$$

$\alpha_{HI}^{(2)}$ is the recombination cross-section to the second excited atomic level and has the value $2.6 \times 10^{-13} T_4^{-0.85} \text{cm}^3 \text{s}^{-1}$, with T_4 , the gas temperature in units of 10^4K . For this calculation they assume $T = 10^4 \text{K}$. Although not very accurate, it gives a lower

limit on the recombination cross-section, $\alpha_{HI}^{(2)}$ (in neutral regions atomic cooling prevents the gas from having a higher temperature).

Similarly the heating rate $\mathcal{H}(r)$, is calculated as a function of the radial distance r using;

$$\mathcal{H}(r) = f n_H x_{HI} \int_{E_0}^{\infty} \sigma(E) \mathcal{N}(E; r) dE \quad (A3)$$

where f is the fraction of the absorbed photon energy that goes into heating through collisional excitations of the surrounding material (Shull & van Steenberg 1985). The function f is fitted in the paper by Shull & van Steenberg (1985) with the following simple fitting formula: $f = C [1 - (1 - x^a)^b]$, where $C = 0.9771$, $a = 0.2663$ and $b = 1.3163$ and $x = 1 - x_{HI}$ is the ionized fraction. This fitting function is valid in the limit of high photon energies, an appropriate assumption for the case at hand. The fitting formula is modified by imposing a lower limit of 11% for the fraction of energy that goes into heating as the proposed fitting formula does not work well at ionized hydrogen fractions smaller than 10^{-4} . And $\sigma(E)$ is the cross-section combining that of hydrogen and helium in the following manner;

$$\sigma(E) = \sigma_H(E) + \frac{n_{He}}{n_H} \sigma_{He}(E) = \sigma_1 \left(\frac{E_0}{E} \right)^3. \quad (A4)$$

Here, σ_1 is a smooth function of energy. The temperature of the IGM due to this heating is determined by the following equation (Madau, Meiksin, & Rees 1997; Zaroubi et al. 2007):

$$\frac{3}{2} \frac{n_H k_b T_{kin}(r)}{\mu} = \mathcal{H}(r) \times t_q. \quad (A5)$$

Here T_{kin} is the gas temperature due to heating by collisional processes, k_b is the Boltzmann constant, μ is the mean molecular weight and t_q is the miniquasar lifetime. This equation assumes that the heating rate due to the absorption of X-ray photons during the miniquasar lifetime is constant. Given the miniquasars lifetime of 3 and 10 Myr and Hubble time at the redshifts we are interested in, cooling due to the expansion of the Universe can be safely neglected. A 10^5 K cutoff on the gas kinetic temperature due to atomic cooling is imposed. Figure A1 shows the kinetic temperature profiles for the 4 cases namely, redshifts of 20 and 10 and lifetimes of 3 and 10 Myrs.

Although the figure shows an overall agreement between the simplistic analytical model and the full RT numerical solution, the analytical approach underestimates the heating by a factor of roughly 3 to 5 in the outer radii. The reason for this is that the helium cross-section is accounted for in the analytical approach (see eq. A4) in a very incomplete fashion whereby the heating stops as soon as hydrogen is completely ionized (eq. A3). In reality this is not the case as heating by high energy photons will continue until also He is fully ionized. Figure A2 shows the cross-sections of neutral hydrogen (dotted line), completely neutral helium (dashed line), singly ionized helium (dot dashed line) all weighted by their abundances. Over plotted on this is the case in which all hydrogen and half of all helium has been completely ionized (50% HeII case). At high energies, like the spectrum of the miniqso under discussion, even this fraction of singly ionized helium provides a substantial cross-section that can capture the photon and convert its energy to heat. Interestingly, looking at Figures 6 and 7 in conjunction with Figures 8 and 9 around a radial distance of 20 - 30 kpc reveals that there is a correlation between the increase in temperature and the corresponding increase in the singly ionized helium species.

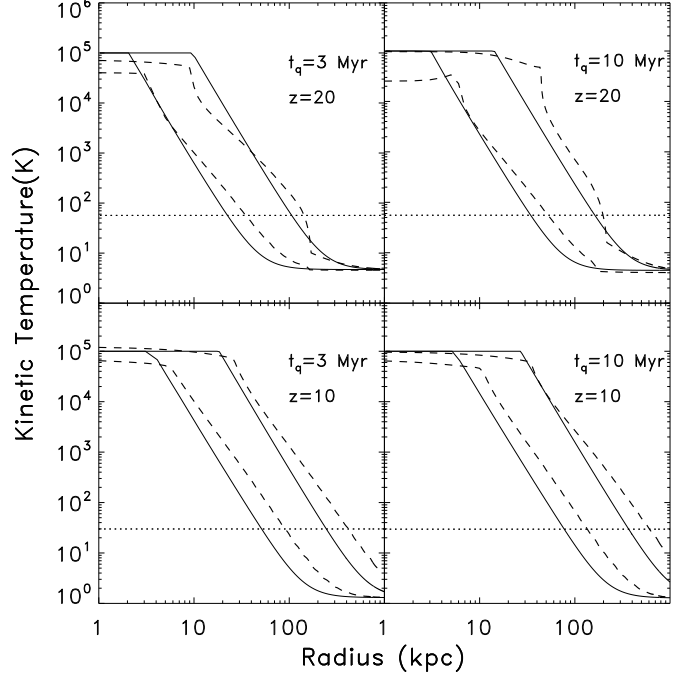


Figure A1. Each panel in this Figure shows a comparison between the model of Zaroubi et al. (2007) and the results of the spherically symmetric radiative transfer code applied to black hole masses, 100 & 10000 M_{\odot} with the same spectral energy distribution. The analytical calculation is represented by the solid line and that obtained from the radiative transfer code is represented by the dashed line. The different panels corresponds to different values of redshift and quasar lifetime ' t_q '.

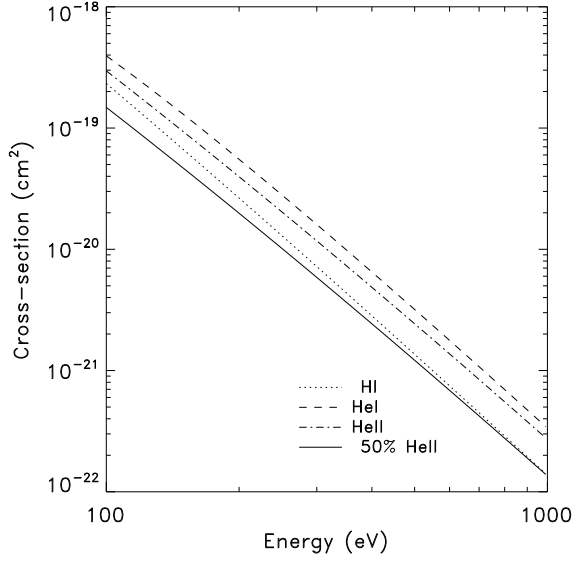


Figure A2. Figure shows the cross-sections (Verner et al. 1996) of neutral hydrogen, neutral helium and singly ionized helium, all weighted by their abundances in the mean IGM. Overplotted is also the 50% singly ionized helium, i.e., all hydrogen has been ionized and 50% of all helium is completely ionized.